Peabody Museum
of Natural History
Yale University
New Haven, CT 06520

POS
6088

Postilla Number 174
1 May 1979

Biogenic Structures of Black Shale Paleoenvironments

Charles W. Byers

MUS. COMP. ZOOL.
LIBRARY
FEB 13 1984
HARVARD
UNIVERSITY

Contents

List of Tables ii
List of Illustrations iii
Abstract iv
Preface 1
Acknowledgments 2
1. **Introduction** 2
Lamination and bioturbation in Recent muds 2
Anoxic marine environment 4
Physical setting 4
Animal life 5
Sediments 6
2. **Investigation** 8
Sonyea Group 8
Stratigraphy 8
Lithology 9
Internal sedimentary structures 9
Pierre Shale and Fox Hills Formation 11
Stratigraphy 11
Lithology and sedimentary structures 14
3. **Biogenic Structures** 17
Burrow morphology 17
Bioturbation trends 18
4. **Paleoenvironments** 19
Sonyea Group 19
Pierre-Fox Hills 22
5. **Summary** 25
Literature Cited 25
Appendix, Locality List 28

List of Tables

1. Schäfer's classification of biofacies 4
2. Hydrographic characteristics of marginal seas in humid and arid climates 7

© Copyright 1979 by the Peabody Museum of Natural History, Yale University. All rights reserved. No part of this publication, except brief quotations for scholarly purposes, may be reproduced without the written permission of the Director, Peabody Museum of Natural History.

List of Illustrations

1. Oxygenation and species diversity (graph). 6
2. Stratigraphy of the Sonyea Group. 8
3. Black shale stratigraphy of the Sonyea Group. 9
4. Correlation chart of Pierre Shale and Fox Hills Formation at the Red Bird Section in eastern Wyoming and the Type Fox Hills Area in northcentral South Dakota 11
5. Columnar section of Lower Pierre Shale at Red Bird, with sampling levels indicated. 12
6. Columnar section of most of Pierre Shale at Red Bird with sampling levels indicated. 13
7. Columnar section of Lower Pierre Shale at outcrop near Chadron, Nebraska. 13
8. Columnar sections of Upper Pierre Shale and Fox Hills Formation in Type Area. . . . 13
9. Columnar section of Little Eagle facies with sampling levels indicated. 14
10. Organic carbon content of shale samples from Red Bird and Type Fox Hills Area. . 15
11. Major burrow forms in shale and mudstone. 17
12. Eastward shift of facies in Sawmill Creek Shale relative to the deltaic episode of the Triangle Formation. 21
13. Conditions of deposition for the Sonyea Group during periods of deltaic progradation which produced the Triangle and Glen Aubrey lobes, and during transgressions which produced the Montour and Sawmill Creek Shale tongues 22
14. A) Conditions of deposition for the Members of the Pierre Shale at Red Bird. 24
    B) Depositional history of the Pierre Basin as inferred from biofacies changes in the Red Bird Section. 24
15. Conditions of deposition for the Upper Pierre Shale and Fox Hills Formation at the Type Fox Hills Area. 25
16. Examples of major Sonyea lithologies. 31
17. Lamination in Sonyea rocks: Lake Erie, Finger Lakes, and Sidney Regions. 33
18. Horizontal fabric in uppermost Niobrara Formation and basal Pierre Shale, Red Bird Section. 35
19. Bioturbation and lamination in Middle and Upper Pierre Shale and basal Fox Hills Formation, Red Bird Section. 37
20. Bioturbation in Upper Pierre Shale and Lower Fox Hills Formation, Fox Hills Type Area. 39
21. Burrow morphologies. 41
22. Bioturbation gradients in Montour and Sawmill Creek Shales. 43

Biogenic Structures of Black Shale Paleoenvironments

Charles W. Byers

(Received 6 September 1974)

Abstract

Identification of specific environments of deposition represented by black shales has been a traditional puzzle for geologists. The present study was undertaken to see whether sedimentary structures, especially biogenic structures, could be used to subdivide the inclusive term "black shale facies."

Because of the prevalence of infauna, modern marine muds are typically bioturbate; only where animal life has been excluded, usually by oxygen deficiency, is the depositional lamination preserved. Fine laminae are characteristic of anoxic water in all modern seas and oceans.

Two ancient black shale sequences were investigated; one, in the Upper Devonian Sonyea Group of New York, provided samples along a thin time-parallel shale tongue; the other, the Upper Cretaceous Pierre Shale and Fox Hills Formation of the Western Interior, permitted vertical sampling of a thick section in a single area.

Similar facies occur in both sequences. The shales can be divided into four biofacies, depending on the amount of biogenic reworking. In the Sonyea Group four facies are encountered from west to east: 1) laminated, 2) bioturbate, 3) mottled, 4) bedded; in the Pierre Shale and Lower Fox Hills these facies occur in the same order upward from the bases of the section. Laminated sediments are thought to indicate anoxic conditions below the mixed layer in a silled basin, probably at depths greater than 150 m. Bioturbate sediments reflect the presence of infauna, living under marginally aerobic conditions in shallower water. The mottled fabric, with larger and more diverse burrows partially obscuring physical sedimentary structures, was produced at still shallower depths. The bedded facies lacks burrows, due to physical reworking in the shallowest zone; these nearshore, agitated waters were probably less than 20 m deep.

This facies pattern defines the bathymetry of the Sonyea Sea: a deep anoxic basin in western New York graded up onto a shelf in the Ithaca area. During the deltaic episodes which alternated with black shale deposition, the shelf water was shallow and fully aerobic, and therefore fossiliferous. Deeper water and marginally aerobic conditions on the shelf were the consequences of a transgression, which shifted anoxic environments eastward from a persistent anaerobic basin. Each shale tongue in the Catskill wedge represents such a transgression.

In the Pierre-Fox Hills section the facies pattern resulted from the gradual filling of an originally anoxic basin. In any one locality bottom conditions changed from anaerobic to marginally aerobic to fully oxygenated and agitated as shallowing proceeded.

The Middlesex is thin, laterally persistent, and probably isochronous, while the Pierre is quite thick, with time-transgressive members. Lateral facies changes in the Middlesex should therefore indicate contemporaneous paleoenvironments within the Late Devonian basin. Vertical changes in the Pierre, on the other hand, would reflect the depositional environment varying through time as the Late Cretaceous basin was filled.

The major lithologic facies of the two shales were already mapped, but the more obscure facies changes based on internal fine structure had not yet been examined. As usual, recognition and interpretation of subtle facies changes demands that a good stratigraphic framework be established first. Since the lithostratigraphy of these two shales was known, they could be sampled quickly.

Facies were defined in this study by means of the fine structure of the shale fabric, especially the biogenic structures: their sizes, abundances, and morphologies. Then, using similar structures from modern seas as guides, it was possible to infer the conditions of deposition in the ancient seas, especially the factors of water depth and oxygenation. In this way the various environments of deposition in the Devonian and Cretaceous basins were recognized, and some of the basin hydrographies inferred.

Preface

The very impressive diversity and ubiquity of life in the sea should prompt paleontologists to inquire into the origin of "unfossiliferous" marine sedimentary rocks. Were the sediments origianally azoic? And if so, what were the conditions that eliminated animal life? One of the means for answering such questions is the study of trace fossils. Trace fossils are better indicators of conditions in the depositional environment than are body fossils, for several reasons.

First, trace fossils are more resistant to diagenetic alteration than are body fossils. While the processes of lithification and leaching may easily dissolve carbonate shells, these processes have little adverse effect on biogenic sedimentary structures. In fact, the effect may even be positive; in well-indurated rock the bedding plane trace fossils are accentuated, and the rock is more easily sectioned for viewing internal burrows.

Second, even benthic body fossils may be added or removed from a given environment by postmortem transport. Trace fossils, on the other hand, are completely *in situ* records of life activities in the sediment.

Finally, and most important, trace fossils commonly record the presence of soft-bodied organisms. In modern seas, the various worm phyla are more widespread and more numerous than heavily calcified forms. Also, the soft-bodied fauna is generally more tolerant of extreme physicochemical conditions and will be found in marginally habitable environments where shelled fauna is reduced or excluded. Thus a lack of fossil shells does not guarantee that the original muds were truly azoic; only when there is also a lack of trace fossils can we be sure that metazoan life was absent.

Of the several facies that have been labelled "barren," black shale has been the most enigmatic. This facies is commonly devoid of body fossils and is usually presumed to be azoic. It was felt that an examination of the trace fossils in black shale might clarify our understanding of the specific conditions of deposition and possibly allow subdivision of the inclusive term "barren facies." For this latter reason, two shales were sampled so that apparent facies changes could be compared and contrasted between different formations. The two shales, the Upper Devonian Middlesex Shale of New York, and the Upper Cretaceous Pierre Shale of the Western Interior, were chosen for special reasons.

First and foremost, the stratigraphy, paleontology, and general environmental settings of the two shales have been recently worked out by Sutton, Bowen, and McAlester (1970) for the Devonian, and by Gill and Cobban (1966) and Waage (1968) for the Cretaceous. Both shales are interpreted as products of deeper water offshore from a generally prograding deltaic complex. Thus shales of similar environments, but widely separated in time, could be compared to each other and to Recent sediments.

Acknowledgments

I have been helped by many people in the course of this work; it is a pleasure to acknowledge their various contributions here.

My three readers, Drs. Donald C. Rhoads, A. Lee McAlester, and Karl M. Waage, have all had a hand in the direction my work has taken, and all three devoted time and attention, providing specialized knowledge as well as general encouragement. In particular, Donald Rhoads introduced me to the study of biogenic structures in sediments and rocks, and suggested the techniques I used in shale collection and preparation.

Lee McAlester provided me with much information on the Devonian section of New York, including the maps and locality data which I relied on in the field.

My advisor, Karl Waage, accompanied me in the field and guided me through the stratigraphy of the Western Interior. His knowledge of the Cretaceous section was invaluable to me; for this and for his active participation in the field work of the Cretaceous collecting, I am very grateful.

Field work was supported by grants from the Charles Schuchert Fund of Yale Peabody Museum and the National Science Foundation, during the summers of 1970 and 1971, respectively.

Finally, it must be noted that my original manuscript has been greatly improved through the efforts of Paul Dombrowski, draftsman, and Catherine Ward, typist.

1. Introduction

Lamination and Bioturbation in Recent Muds

The classic view of mudstone states that it is deposited from suspension in very slowly moving water (Hjulstrom, 1939). Recently it has been suggested that some fine-grained sediments may be laid down by relatively rapid turbidity currents (Piper, 1972), but it is clear that most shales, mudstones, and fine silts are products of deposition in low-energy environments (Allen, 1970). Muds deposited in such physical conditions will be homogeneous, or if there is variation in the supply, laminated. Laminae will be horizontal, parallel, and continuous laterally, reflecting the quiet water environment.

Excluding turbidity current deposits, most Recent marine sediments of the neritic zone and deeper are silts and clays deposited from suspension in quiet water (Allen, 1970, p. 174). Lamination in these sediments is rare, however, because of the activities of the infauna. Although the effects of burrowing infauna on marine sediments have been discussed theoretically for many years, it is only recently that they have been recognized in the field.

It was known in the last century that deposit-feeding infauna rework marine muds: "the matter forming the bottom of the sea is being continuously passed and repassed through the bodies of numerous tribes of animals which demonstrably subsist on the mud and its contents" (Buchanan 1891, quoted by Twenhofel, 1939). Twenhofel stated clearly in 1939 that sediments will be reworked by infauna unless bottom conditions are hostile to life, and Dapples (1942) predicted that bur-

rowing infauna such as annelids and holothurians would strongly alter marine sediments, the greatest change being found in areas of optimum living conditions. This prediction has been borne out in numerous studies of the sedimentology of Recent marine sediments (for example, Scruton, 1955; Moore and Scruton, 1957; Nota, 1958; Van Straaten, 1959; Allen, 1964, 1965; Coleman, Gagliano, and Webb, 1964; Coleman and Gagliano, 1965; Reineck, 1967). In all cases it was found that a nearshore zone, characterized by rapid sedimentation or physical reworking, or both, was dominated by sedimentary structures, especially bedding and cross-bedding, whereas offshore in deeper, quieter water the sediments were churned by an abundant benthos, and physical structures were obliterated.

Shelf sedimentation in Recent seas is actually dominated by biological activity. Rhoads (1963, 1967) measured the rates of sediment reworking by organisms in intertidal and subtidal environments and found that intertidal sediments are completely reworked by large vertically-burrowing polychaetes to a depth of 10 cm; maximum depth of burrows is 30 cm. Turnover of the upper 10 cm may require several months; thus in areas of strong physical processes, the bedding of the sediments may be maintained. At subtidal depths the biologic reworking is carried on in the top 2–3 cm of the sediment, by protobranchs, holothurians, and small polychaetes. Sediments are completely turned over to a depth of 2 cm annually. Since the physical sedimentation processes are minimal, biological activity homogenizes the muds. Rhoads found, for example, that in Buzzard's Bay and Long Island Sound *Yoldia limatula*, which constitutes only 10% (by number) of the total fauna, is capable of reworking the annual deposition at least twice a year. In such cases, no primary sedimentary structures would be preserved.

Preservation of physical sedimentary structures in quiet water muds requires that infauna be excluded, that the muds themselves be azoic. This condition seems to be rare in modern shelf seas. Organisms can be blocked from colonizing areas of rapid sedimentation or reworking, such as in deltaic and shallow subtidal zones, or deeper water subjected to common turbidity current flows; but in normal shelf muds not being subjected to high-energy rigors, chemical rather than physical mechanisms are more likely to exclude animal life in the sediments. Extremes of salinity are certainly effective in restricting the distribution of many marine families, but mechanisms are lacking for altering salinity strongly enough to produce actual azoic bottoms. In the ocean, salinity (at 35%) never varies by more than a very few parts per thousand (Pearse and Gunter, 1957). Changes are more prevalent and larger in semienclosed seas and bays since runoff or evaporation there can outstrip mixing to lower or raise salinity respectively. In general, changes in salinity will restrict stenohaline species, thus lowering diversity; but actual elimination of benthos requires a very great change, greater than those found in modern seas.

If salinity variations are an unlikely agent for producing azoic waters, lack of oxygen is a strong candidate. All metazoans require oxygen; if it is lacking continuously in marine waters, they will be azoic except for anaerobic bacteria.

Since oxygen is so all-important to the marine community, variations in oxygen due to hydrographic conditions have been used to classify marine environments. Schäfer (1962) reasoned that both oxygen content and sedimentation rate are products of the degree of water movement, which thus became the basic factor in his classification. He divided the entire marine environment into five first-order biofacies based on degrees of water movement. The three vital and two lethal biofacies are listed in Table 1, along with their salient features and an example of each. Secondary characteristics such as light, temperature, and salinity can be superimposed on the first-order biofacies to subdivide them.

It should be noted that the two lethal agents discussed above, rapid sedimentation or re-

working, or both, and lack of dissolved oxygen, play end-member roles in the classification. Although all of Schäfer's biofacies can be recognized in the sedimentary record, the Lethal Isostrate environment is of greatest pertinence to this study, since it deals entirely with quiet water and fine sediments and their structure. This anoxic environment will be examined more closely in the following section.

Anoxic Marine Environment

Physical Setting

In most of the world ocean and in seas as well the water is kept oxygenated by lateral and vertical circulation. However, in the case of a silled basin, lateral circulation is limited, and

Table 1.
Schäfer's classification of biofacies (after Schäfer, 1962).

Biofacies	Primary Characteristics	Example
1. Vital Nonstrate	Produced by the materials from a persistent biocoenosis; bedding lacking.	Coral reef
2. Vital Heterostrate	Many early-destroyed benthic biocoenoses; thanatocoenoses; minor erosional events common.	Shallow shelf
3. Lethal Heterostrate	Rich thanatocoenoses; large erosional unconformities; no benthic biocoenosis present.	Littoral and sublittoral with strong physical reworking
4. Vital Isostrate	Stable benthic biocoenosis; thanatocoenoses of nekton and plankton; no erosional loss of strata, although strata are usually deformed or destroyed by bioturbation.	Shelf below zone of normal physical reworking
5. Lethal Isostrate	Rich thanatocoenoses of nekton and plankton; no benthic biocoenosis; no erosion or bioturbation.	Anoxic basin

vertical movement and diffusion may be unable to replenish the oxygen supply of water below the sill. This condition is especially likely if large amounts of organic matter are delivered to the basin, as when the surface waters are highly productive. Then oxygen use quickly outstrips supply, and the basin waters and sediments become anoxic. It is also worth noting that sediments may have very low dissolved oxygen (d.o.) values even when the overlying waters are well oxygenated.

Silled basins such as those of the California borderland have d.o. values of 0.2–0.4 ml/l (Emery, 1960); still more extreme is the Black Sea, where water below the 200 m sill depth is totally lacking in oxygen and is charged with H_2S, due to the activities of anaerobic bacteria (Caspers, 1957). In general, marginal seas such as the Black Sea or the Baltic are more likely to vary in d.o. than ocean basins because the effects of runoff or evaporation magnified in a shallow restricted seaway.

Animal Life

Normal oxygenation in the ocean surface waters is about 7 ml/l, and diminishing this to about 2 ml/l has little effect on marine communities. However, further lowering causes changes in the fauna; organisms become generally smaller in body size, numerically less abundant, and more monotonous, tending toward domination by small, vermiform infaunal animals. Thus 2–7 ml/l dissolved oxygen can be considered sufficient oxygenation for most shelf phyla. Values of 0.1–1.0 ml/l d.o. were termed "dysaerobic," and 0–0.1 ml/l d.o. "anaerobic" by Rhoads and Morse (1971). It is within the dysaerobic and anaerobic environments that major changes in benthic communities are encountered.

The various effects of oxygen deficiency have been studied in the laboratory (Theede et al., 1969), as well as in the field (Fenschel and Riedl, 1970; Hartman and Barnard, 1958, 1960; Parker, 1964a, b). In addition, the theoretical relationships between metazoan size and dissolved oxygen in the environment were investigated by Raff and Raff (1970).

Both field and laboratory results indicate similar consequences of a reduction of dissolved oxygen. Theede et al. (1969) documented the resistance of various invertebrates to low oxygen and the presence of hydrogen sulfide; they found that decreasing oxygen selectively eliminated certain ecologic groups. Inhabitants of soft substrates, such as burrowing molluscs and polychaetes, were more resistant than animals inhabiting hard substrates.

Other evidence that metazoa can adapt to low-oxygen environments was provided by Fenschel and Riedl (1970). In their investigation of the deeper anaerobic layers in nearshore marine sediments, they found several species of metazoans, which may be aerobes in the anoxic layers on a short-term basis, or actual facultative anaerobes. These animals are members of the most primitive worm phyla, platyhelminthes and aschelminthes. All are tiny, less than 0.1 mm in diameter.

Similar animal types and sizes were reported by Hartman and Barnard (1958, 1960) from benthic communities in the dysaerobic deep basins off Southern California. Oxygen is very low in the nearshore basins, slightly higher in the deeper offshore basins, and at full saturation value in the shelf waters. Oxygen reduction in the basins strongly decreases the benthic biomass, as shown by the following data from Hartman and Barnard:

Biomass (g/sq.m.)	Environment
4–5	Nearshore basin
8.7	Offshore basin
4000	Shelf region

Biomass reduction is due to both impoverishment of populations and small animal size. In particular, large shelf species, especially shelled molluscs, are rare in the basins. Shelf species occurring there are commonly smaller than normal or incompletely developed; sexual maturity is rare. Many are probably immigrants from the shelf, rather than

part of a viable basin population. Overall, animal size in the basins is small; animals larger than 2 mm long or 1 g mass are rare. Heavy shells are greatly reduced or absent in the basins as well (see Rhoads and Morse, 1971, for a discussion of the physiological problems of maintaining shells under dysaerobic conditions).

The decreased diversity in basin faunas is shown by the comparative increase in importance of wormlike organisms. At shelf depth the polychaete-crustacean ratio is 1:1, while at basin depth it has risen to 8:1, and in the basins sipunculids are more abundant by fivefold than their shelf populations. Hartman and Barnard conclude that the basin environment strongly favors wormlike infaunal animals over epifauna, especially shelled epifauna. Of the total of 1106 shelf species in the region, only 9% are found at basin depth. The basins are also less diverse than normal abyssal and bathyal faunas, however, and the nearshore basins are less diverse than the deeper (and more highly oxygenated) basins. Since the basins actually have a higher nutrient influx than normal abyssal areas, the diversity drop appears to be due to oxygen reduction alone.

Parker's exhaustive study of the animal distributions in the Gulf of California confirmed the trends discussed above (Parker, 1964a, b). Clearly defined diversity gradients were observed in sampling from normally oxygenated waters down into the Oxygen Minimum Zone. As the graphs in Figure 1 show, shelled epifauna are selectively reduced when dissolved oxygen drops below 2.0 ml/l, and they are generally absent at d.o. below 1.0 ml/l. Polychaetes and aschelminths are less strongly affected, as are the deposit-feeding small bivalves. Thus the benthos of the Oxygen Minimum Zone is dominated by small, burrowing infauna, with thin shells or lacking shells entirely, just as in the dysaerobic California basin environment.

Sediments

A variety of effects on the sediments is produced by dysaerobic or anaerobic conditions in the bottom waters or muds, or both. First and foremost, since the benthos is severely restricted or eliminated, bioturbate structure is absent. Instead, the primary sedimentary structures produced during deposition are maintained intact. Since anoxic waters are always quiet waters, sedimentation is dominated by pelagic processes. Structures such as ripples, cross-lamination, and scour-and-fill are absent, except for bottoms affected by turbidity currents; the sediments will otherwise be uniform clays or silty clays. Changes

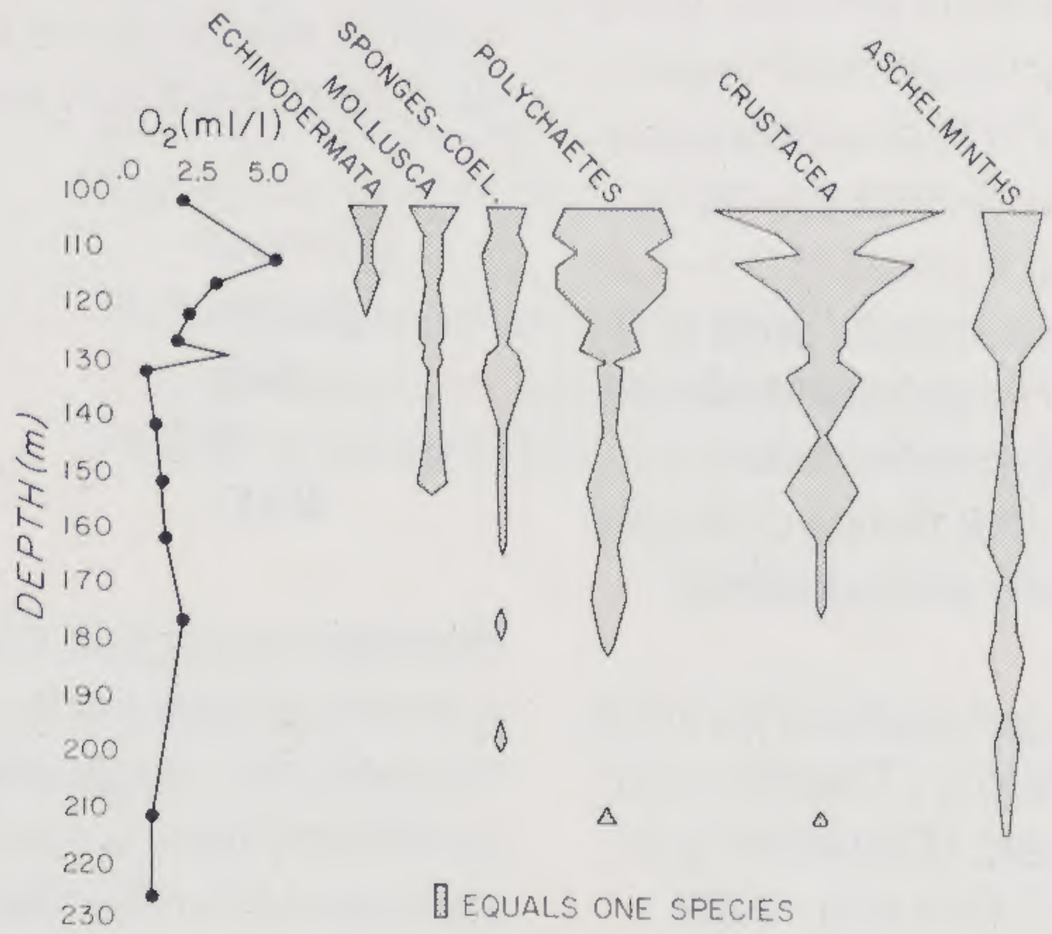


Fig. 1
Oxygenation and species diversity. Graph showing the effect of lowered dissolved oxygen on species diversity (data from Parker, 1964b). Abbreviation: COEL. = Coelenterata.

in sediment supply will result in horizontal layering, generally quite continuous over large distances. For example, Ross, Degens, and MacIlvaine (1970) reported that sequences of laminae only 1 mm thick could be correlated across 1000 km of the Black Sea basin. Such fine lamination as this is the prime characteristic of anoxic sediments and has been found in all the anaerobic environments investigated: the Gulf of California (Revelle, 1950; Calvert, 1964, 1966; van Andel, 1964); the California borderland basins (Emery and Hülseman, 1962; Hülseman and Emery, 1961); the Black Sea (Ross, Degens, and MacIlvaine, 1970); and the Baltic Sea (Segerstrale, 1957; Siebold, 1970). All these marine basins contain large areas of laminated lutile in deep, stagnant water zones.

More local areas of laminated sediment have been recorded from anaerobic bottoms in semirestricted bays and fjords: in the Adriatic (Seibold, 1958), in Vancouver Bay (Gross, et al., 1963), in the Clyde Sea (Moore, 1931), in Scandinavian fjords (Strøm, 1955). In all cases, alternation of layers is caused by seasonal changes in the sediment source: in the biogenic component, plankton blooms, or in the detrital component, variable runoff.

The largest areas of laminated sediment are found in semirestricted marginal seas since these are the easiest to stagnate. Seibold (1970) developed a model of sediments, hydrography, and biofacies in marginal seas under various climate regimes. He showed that generally humid climates (large runoff) produce bottom stagnation and all its consequences, whereas generally arid conditions produce an unstable water column, oxygenation at depth, and all its consequences. Using the Baltic and the Persian Gulf as end-members, Seibold showed that their major differences in salinity, temperature, water density, dissolved oxygen, sediment chemistry, sedimentary structure, and benthic life are all controlled by climate (as shown in Table 2).

Table 2.

Hydrographic characteristics of marginal seas in humid and arid climates (after Seibold, 1970).

Humid region	Hydrographic characteristic	Arid region
outflowing	surface current	inflowing
inflowing	bottom current	outflowing
clear-cut except for winter mixing	water layering	less clear
	Bottom water characteristic	
low	salinity	high
low	oxygen content	high
high	nutrient content	low
	Sediment character	
low	carbonate content	high
high	organic carbon	low
high	metal content	low
low or absent	bioturbation	high

2. Investigation

Sonyea Group

Stratigraphy

The Upper Devonian Sonyea Group of New York State contains two progradational deltaic complexes, each bounded by thin isochronous black shale units. The upper shale (Moreland) is included in the succeeding West Falls Group; the lower and middle shales (Montour and Sawmill Creek) are considered as basal and mid-Sonyea. West of Ithaca the deltaic clastic wedges pinch out, and the Montour and the Sawmill Creek coalesce to form the Middlesex black shale of the Lake Erie region (see Fig. 2). The stratigraphy of the Sonyea

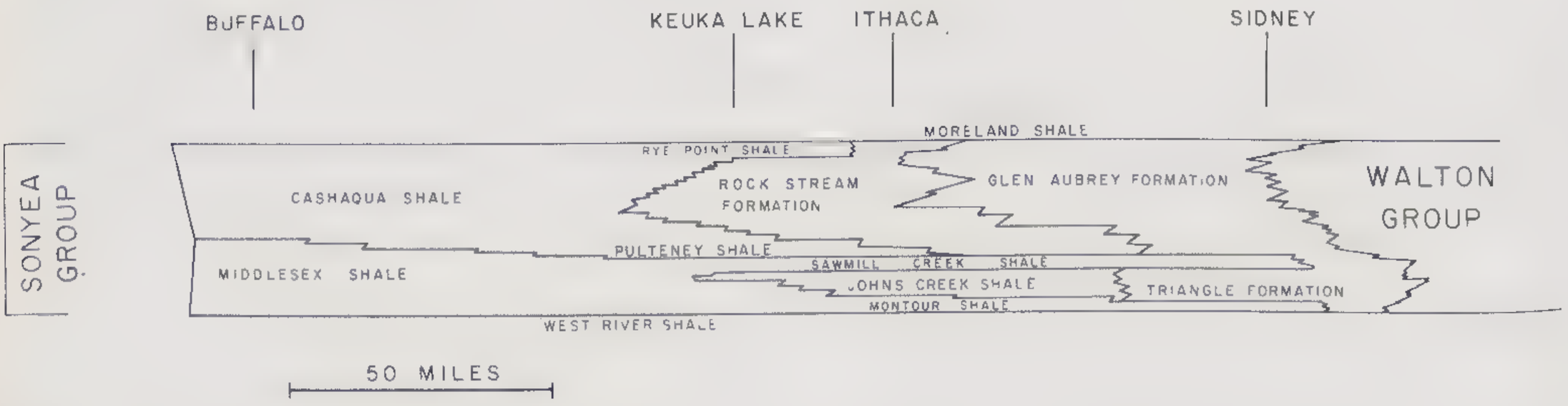


Fig. 2
Stratigraphy of the Sonyea Group (after Rickard, 1964; and Sutton, Bowen, and McAlester, 1970).

was described by Colton and deWitt (1958) and by Sutton (1960). The stratigraphy of the entire Upper Devonian of New York, and its correlation by means of black shales, was summarized by Sutton (1963). Rickard's (1964) chart correlates all the New York Devonian. Finally, Sutton, Bowen, and McAlester (1970) refined the stratigraphy of the Sonyea and provided an environmental analysis. They named the two deltaic complexes, the lower Triangle Formation and the upper Glen Aubrey Formation, and defined the various deltaic subenvironments by means of lithology and sedimentary structures.

Abundant benthic invertebrate fossils in the two formations indicate that normal marine conditions prevailed during their deposition. However, the Montour and Sawmill Creek black shales, and their westward equivalent, the Middlesex, are predominantly unfossiliferous.

Occasional protobranch bivalves are the only benthic fauna in the eastern shales, and Sutton (1960) reported only *Styliolina fissurella* (pteropod) and *Lingula spatula* from the Middlesex. Although Sutton, Bowen, and McAlester (1970) interpreted the black shales as representing periods of transgression, the detailed environmental conditions during the Montour and Sawmill Creek time were not known. Nor was there information as to the lateral facies changes within the shale tongues. The present study was undertaken to more closely delineate the conditions of deposition in the two shales; biogenic sedimentary structures were mapped in order to demonstrate the lateral facies changes in sedimentary environments.

The black shales crop out along an east-west belt over 200 miles long, from Sidney, N.Y., to Lake Erie. Commonly the shale beds are thin, less than a meter in the easternmost exposures, then gradually thickening to a maximum of 25 m in the western Finger Lakes area, and then again thinning to about 2 m on the shore of Lake Erie (Colton and DeWitt, 1958).

Since the black shale tongues are thought to be isochronous, lateral facies changes would reflect actual environmental changes in various parts of the sedimentary basin at a given "instant" of Late Devonian time. Fortunately, the outcrop band is nearly at right angles to

the depositional strike, so onshore-offshore gradients in facies should show up clearly. Accordingly, shale samples were taken at a series of 29 localities in the Montour and Sawmill Creek and the equivalent Middlesex, as diagrammed in Figure 3; the exact localities are listed in the Appendix.

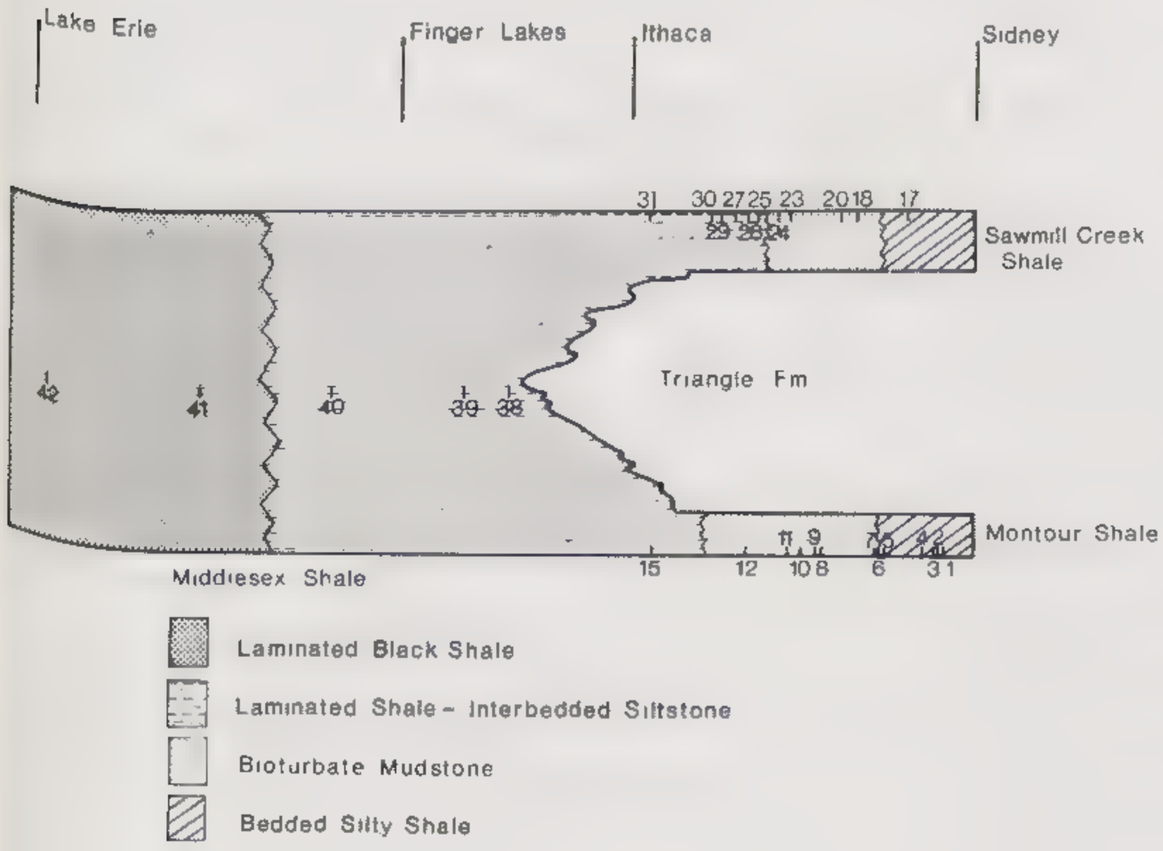


Fig. 3
Black shale stratigraphy of the Sonyea Group, showing sampling locations and the four major lithologies present in the transect.

Lithology

The black shales are actually tongues of rocks with varying colors, from true black to gray; and with varying grain size, from nearly pure carbonaceous clays to nearly pure siltstones; and with varying fabrics, from perfectly fissile to massive. In general the three qualities are linked; thus black, fissile claystone or gray, massive silty mudstone. Furthermore, the qualities vary geographically; the two rocks described above are accurate end-members for the west and east of the outcrop belt respectively.

Superimposed on this west-east gradient there is a secondary geographic variation in lithology, namely changes in the type of rock interbedded with the true shale. At Localities 42 and 41 in the Lake Erie Region the Middlesex Shale is a coherent unit, nearly pure black, fissile claystone. Then from Locality 40 to a point east of Ithaca (Localities 15 and 25) the black shales are intimately interbedded with layers of cross-laminated siltstones. These siltstone layers vary in thickness from a centimeter or two up to 30 centimeters or more. Sole markings, generally strongly linear groove casts, are common in these silts.

A third type of associate rock is seen in the area east of Ithaca where the black shales bound the fossiliferous segments of the Triangle and Glen Aubrey Formations. The shale tongues, becoming more gray, silty, and massive, are less well defined and grade at the contacts into gray, fossiliferous mudstone. It is here that occasional fossils are found in the shale themselves.

Finally, a fourth change is seen in the extreme east, near Sidney, where the black shales are very thin and interbedded with unfossiliferous silts and sands which are commonly ripple-marked and cross-bedded. The distribution of the four lithologies is shown in Figure 3, and examples of the lithologies themselves are shown in Figure 16.

Internal Sedimentary Structures

Since shales are products of deposition in quiet water, it would be expected that physical sedimentary structures would be few. The principal structure is primary lamination, produced by changes in sediment supply, or penecontemporaneous deformation of these laminae, by slumping or loading.

However, a variety of biogenic structures have been found in the Sonyea shales. Only the overall geographic patterns in structures will be discussed here; the actual burrow morphologies will be described below in a comparison with similar structures in the Cretaceous Pierre Shale.

Geographic variations in bioturbation show up clearly in the Sonyea shales. For their description, the four-part zonation of the outcrop belt will again be used.

1. The Lake Erie Region The Middlesex Shale here shows absolutely no traces of biological disturbance of primary laminae.

Furthermore, no trace of physical disturbance, such as rippling or subaqueous slumping, was observed. Vertical sections of the shale show distinct fine laminae. The rock fabric itself is characterized by a parallel horizontality of platy minerals and carbonaceous flakes. The laminae are alternations of dark carbonaceous clay and lighter silty clay. Light laminae were unaffected by HCl, but were etched by HF; microscopic examination shows the light laminae to be composed of detrital grains (also cf. Sutton, 1960).

All laminae are very thin, usually a fraction of a millimeter, and are very well defined and perfectly horizontal across tens of centimeters (see Fig. 17).

At the Sturgeon Point section nearly the entire Middlesex is exposed, and vertical stratigraphic sampling was possible. Basally, just above the West River contact, the shale is dark carbonaceous clay. No silty laminae are present in the lowest centimeters of the section. When they make their appearance, a few centimeters above the contact, they are thin (0.1–0.25 mm thick). In samples from the middle of the shale, these silt laminae have expanded to as much as 1.0 mm in thickness, although the average light-dark laminae pair is only 0.25 mm. Near the upper contact of the shale, the alternating zones are still present, but the silt laminae are not nearly so large or conspicuous. The change in laminae structure is shown in Figure 17.

2. The Finger Lakes Region Lamination is characteristic in the eastern Middlesex and western Montour and Sawmill Creek as well. Again there are no traces of biological activity; in some of the shales, however, the laminae are slightly deformed physically. Instead of parallelism, the laminae may be slightly wavy, or even interrupted. In addition, the alternating silt-rich and clay-rich bands are thicker in the rocks of this area; each band is at least 1.0 mm thick and may be as much as 3.0 mm (see Fig. 17). However, laminae are not always continuous; instead they tend to be diffuse or "beaded."

Where the laminated shales are overlain by silt layers several centimeters thick, there may be disturbance along the contact such as incipient flame structure (Fig. 17, *H*). The tops of these silt beds are gradational back into laminated clays, however, with no disturbance along the contact and no deformation of laminae in the overlying clay (Fig. 17, *I*).

3. The Chenango Region It is here that biogenic structures first appear in the black shales. Generally, biological activity has destroyed all traces of primary lamination; in a few cases remnants of bedding are preserved, however. The bioturbation takes several forms, varying from burrows superimposed on well stratified layers, through mottling of layers into a marbled lithology, to a complete homogenization of the rock fabric, depending apparently on the relative rates of biogenic reworking and the processes of physical stratification. The varying degrees of bioturbation are shown in Figure 22.

4. The Sidney Region The easternmost black shales are structureless internally. Although the rocks are fissile, they tend to split into large platy fragments (0.5–1.0 cm thick) along bedding planes which show evidence of current action. Parting lineation is common in all the shales and siltstones of the Sidney Region; in addition, the silts are generally rippled and cross-laminated, while the shale beds are homogeneous.

Bioturbation is mainly absent, as is the depositional lamination (primary lamination) of the western shales. Current bedding and parting lineation in samples from the Sidney Region are shown in Figure 17.

It is noteworthy that where shale overlies a silt layer, there is a zone of cross-lamination of silt and clay extending upward into the shale. This is in contrast to the upper contacts of silts in the Finger Lakes Region where the transition from silt to clay is sharp and perfectly planar (cf. Fig. 17, *I* and *L*).

Pierre Shale and Fox Hills Formation

Stratigraphy

The Upper Cretaceous Pierre Shale outcrops over a wide area in the Western Interior of the United States and Canada. It overlies the Niobrara Formation and is itself overlain by the Fox Hills Formation. South and west of the Black Hills the Pierre is divided into seven members. East and northeast of the Hills other members are recognized, especially in the Upper Pierre (see Fig. 4 for correlated sections).

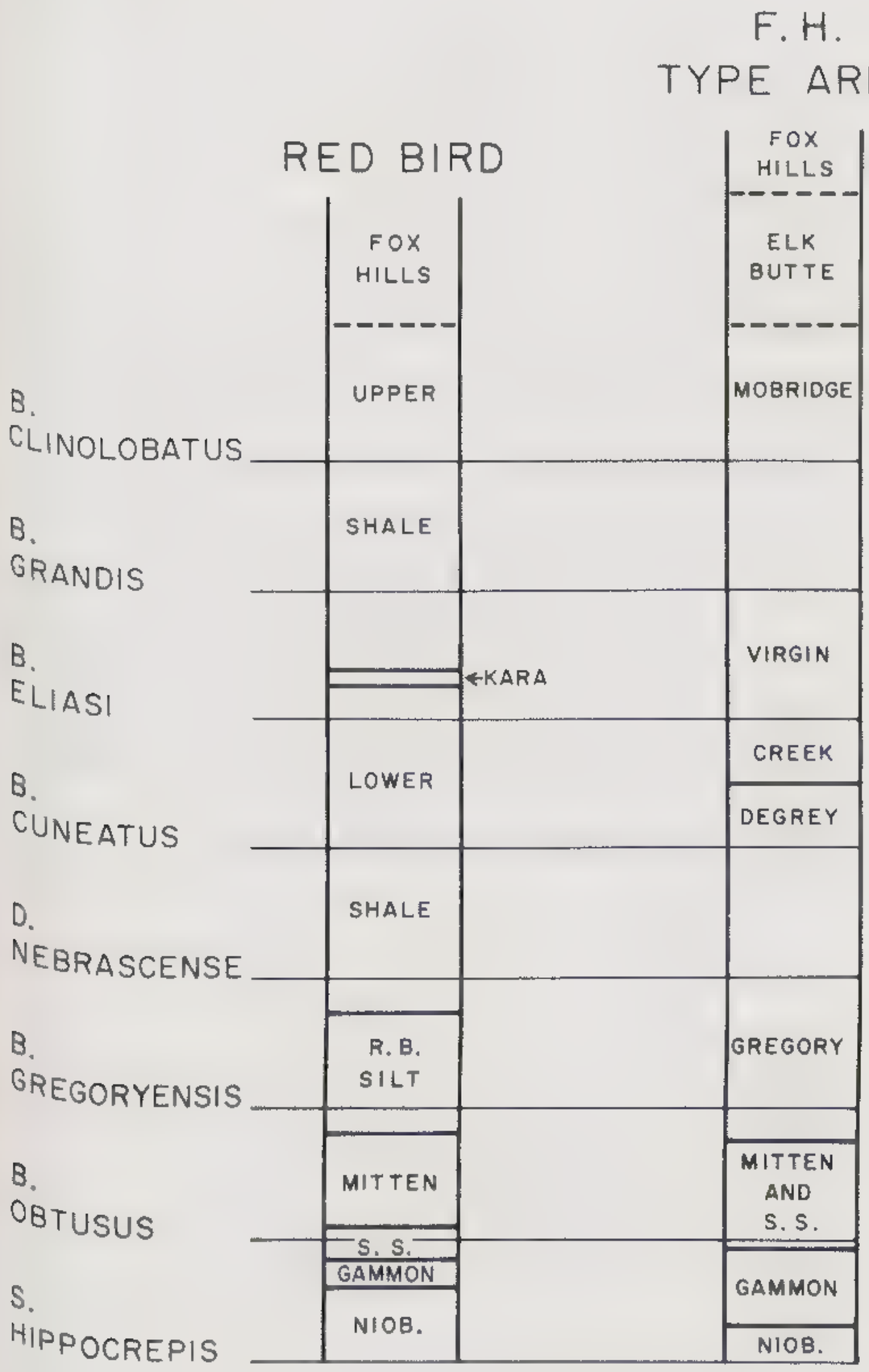


Fig. 4
Correlation chart of Pierre Shale and Fox Hills Formation at the Red Bird Section in eastern Wyoming and the Type Fox Hills Area in northcentral South Dakota (after Gill and Cobban, 1966). Only selected baculite range zones are shown. Abbreviations: F.H. = Fox Hills; S.S. = Sharon Springs.

The Pierre of the Northern Plains is a completely marine shale deposited in the Late Cretaceous seaway that stretched from the Gulf of Mexico to the Arctic. The overlying Fox Hills is a complex of marine siltstones and sandstones produced by the infilling of the seaway in Latest Cretaceous time. At the Red Bird section of the Pierre in eastern Wyoming, Gill and Cobban (1966) define the Pierre-Fox Hills contact at the base of the first major sandstone. Northeast, in the Fox Hills Type Area in west-central South Dakota, Waage (1968) places the base of the Fox Hills at the first influx of silt into the predominantly clayey shale of the Upper Pierre. The Lower Fox Hills in the Type Area is thus lithologically equivalent (silty mudstone) to the Upper Pierre at Red Bird. Consequently, this study of the sedimentary structures of the Pierre includes sampling from the Lower Fox Hills in South Dakota. The Pierre Shale at Red Bird was completely measured and described by Gill and Cobban (1966). The section exposes the entire Pierre (over 3100 feet thick) on the side of the Old Woman anticline. Gill and Cobban recognize seven members; from the base:

- Gammon Ferruginous Member—dark gray, platy shale; siderite concretions; unfossiliferous.
- Sharon Springs Member—black, fissile, splintery shale; rich in organics and bentonite beds; vertebrate fossils locally abundant.
- Mitten Black Shale Member—softer, dark gray to black flakey shale; fossiliferous concretions in upper part.
- Red Bird Silty Member—gray, silty mudstone; fossiliferous concretions throughout.
- Lower Unnamed Shale Member—light to dark gray mudstone; fossiliferous concretions throughout.
- Kara Bentonitic Member—silty, bentonitic mudstone; fossiliferous concretions present.
- Upper Unnamed Shale Member—light gray, silty to sandy mudstone; fossiliferous concretions common.

Gill and Cobban interpreted the overall depositional environment of the Pierre seaway,

mainly through the use of regional ammonite distributions and a general analysis of sedimentation patterns. They noted that intertonguing sandstone beds are lacking, indicating that the shoreline of the seaway was far to the west during much of Pierre time. Gill and Cobban put the water depth at greater than 60 meters for Gammon and Sharon Springs deposition, and then shallowing to considerably less than 60 meters during the deposition of the members above.

In the Missouri Valley area of South Dakota the Pierre Shale is subdivided differently. The basal black shales (Gammon, Sharon Springs, Mitten) persist, but the upper silts and shales are replaced by a sequence of calcareous and siliceous shales: the Gregory, Virgin Creek, Mobridge, and Elk Butte Members (see Fig. 4).

In the Type Fox Hills Area, the Mobridge and Elk Butte Members form the top of the Pierre, the temporal equivalents of the upper part of the Upper Shale at Red Bird:

Mobridge Member—gray calcareous shale; baculite fossils in lower part only.

Elk Butte Member—dark gray, finely silty shale, unfossiliferous except for linguloid brachiopods and arenaceous forams.

The overlying Fox Hills Formation was subdivided into several members and lithofacies by Waage (1968):

Trail City Member (Lower Fox Hills)—clayey siltstone with two roughly east-west lateral facies.

Irish Creek facies—west and southwest in the Type Area; thin bedded silt and clay; unfossiliferous.

Little Eagle facies—east and northeast in the Type Area; mixed clayey siltstone; bedding rare; fossiliferous concretions abundant.

Waage (1968) provided an environment interpretation of the Upper Pierre and the Fox Hills sediments: the uniform lithology of the shales in the Mobridge and Elk Butte Members indicates a low energy, probably offshore, setting. But the scant faunas of the upper Mobridge and the entire Elk Butte imply that normal marine conditions were not in effect. The Trail City, with its influx of silt and lateral facies changes, suggests stronger current regimes and nearby shorelines. Abundant faunas and sediments that appear to be biogenically mixed occur in the Little Eagle, evidence that conditions were hospitable for marine life. The well-bedded and barren Irish Creek sediments lie peripheral to the Little Eagle area; apparently, benthic life was rare in this peripheral zone.

Shale samples were taken at three areas in the Northern Plains; the Red Bird section, the Pierre outcrops on the Nebraska-South Dakota line (north of Chadron, Nebraska); and the Type Fox Hills Area.

Red Bird, Wyoming. Shale was collected at two localities in the Red Bird section. The Gammon and Sharon Springs were intensively sampled in the nearly flat-lying beds on the plunging nose of the Old Woman anticline. The section was measured with steel tape and hand-level, and the sampling locations noted (see Fig. 5). The rest of the Pierre was sampled at exposures, chiefly in deep gullies, along Traverse A of Gill and Cobban (1966). Sampling stations

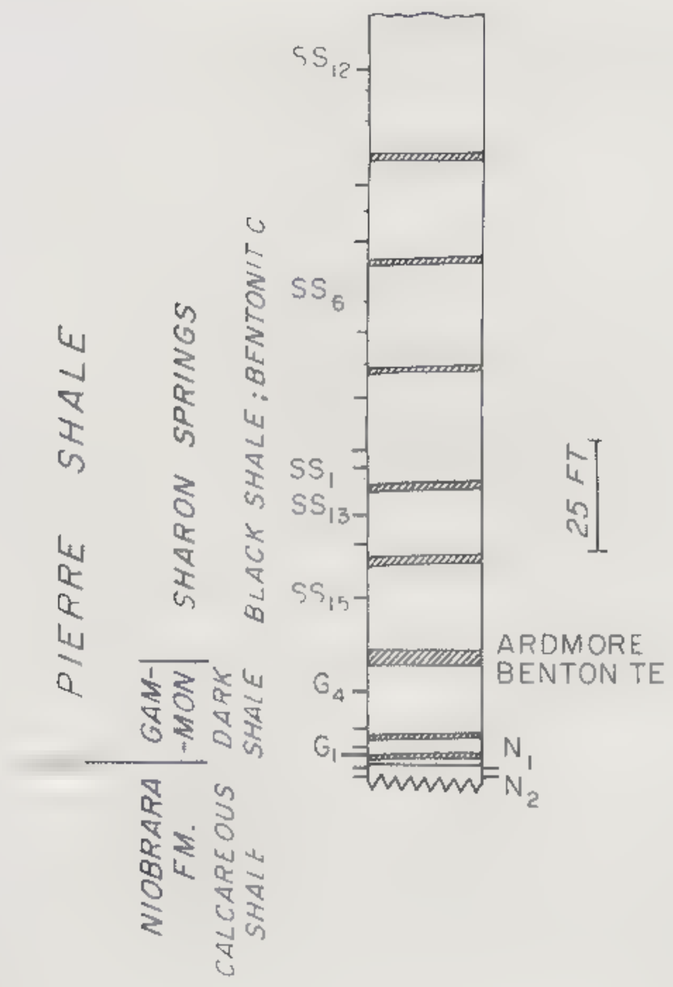


Fig. 5
Columnar section of Lower Pierre Shale at Red Bird, with sampling levels indicated.

for this traverse are shown on the stratigraphic column in Figure 6.

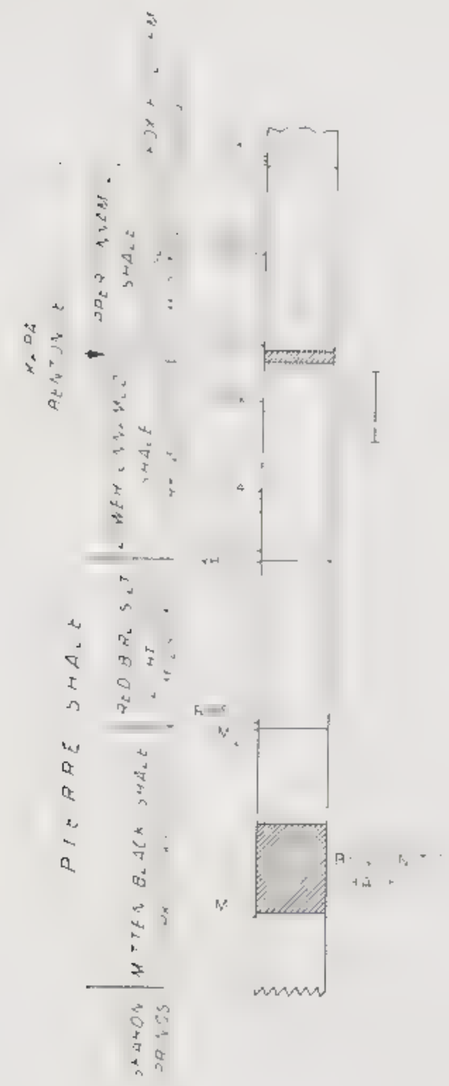


Fig. 6
Columnar section of most of Pierre Shale at Red Bird with sampling levels indicated. (Section is Traverse A of Gill and Cobban, 1966, and is drawn from their measured section.)

Chadron, Nebraska. The Lower Pierre crops out in a prominent ridge just north of the Nebraska-South Dakota state line in Shannon County, South Dakota. Dunham (1961) measured this section and identified the shale as the Sharon Springs Member. In fact, most of the Gammon and Sharon Springs are exposed, and the thicknesses, lithologies, and fossil contents are nearly identical to the basal Pierre at Red Bird. The section was remeasured with Jacob's staff and the sampling positions noted (see the stratigraphic column in Figure 7 for locations).

Type Fox Hills Area. Collections of the Mobridge Member were made at two localities, on Whitehorse Road east of State Highway 63 and in the northern bluffs on the Moreau River slightly west of Highway 63. Exposures of the Mobridge are not good in this area, due to rapid weathering and slumping of the shale, but the sampling locations were placed with reference to the Moreau

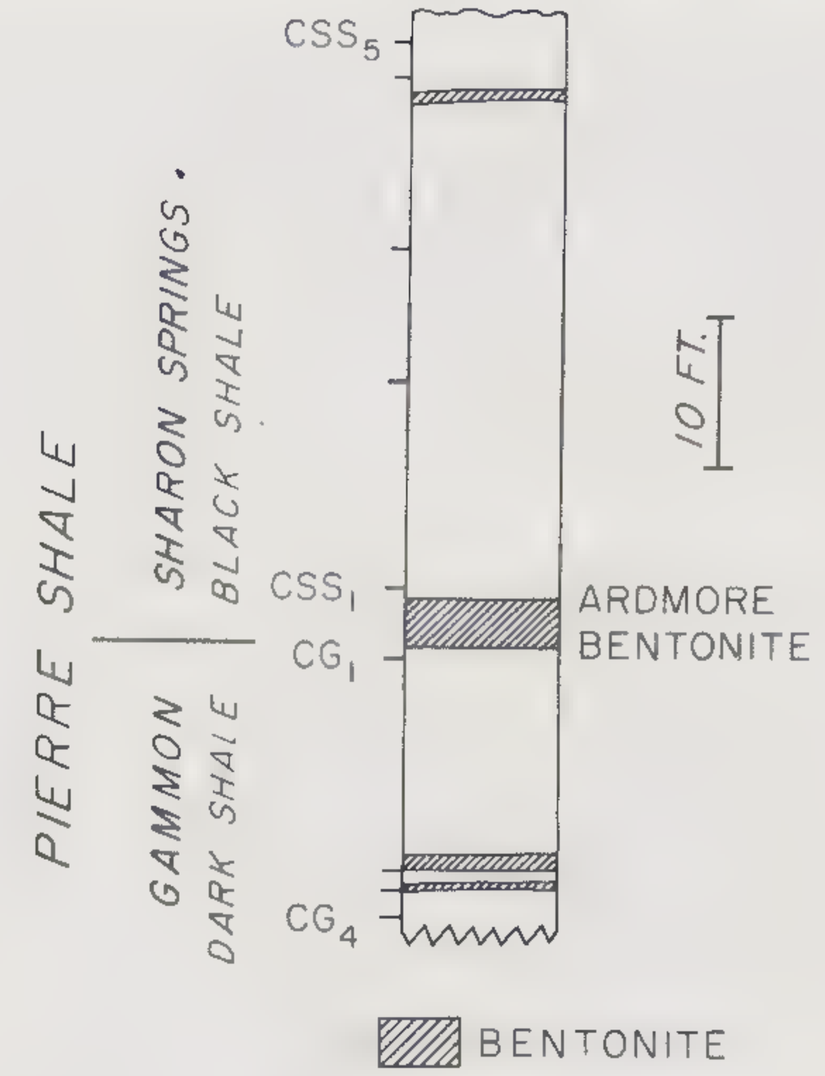


Fig. 7
Columnar section of Lower Pierre Shale at outcrop near Chadron, Nebraska. Sampling levels indicated.

Bridge faunule in the upper Mobridge, a zone of scattered concretions containing bivalves and ammonites. The sampling sites are shown on the columnar section in Figure 8.

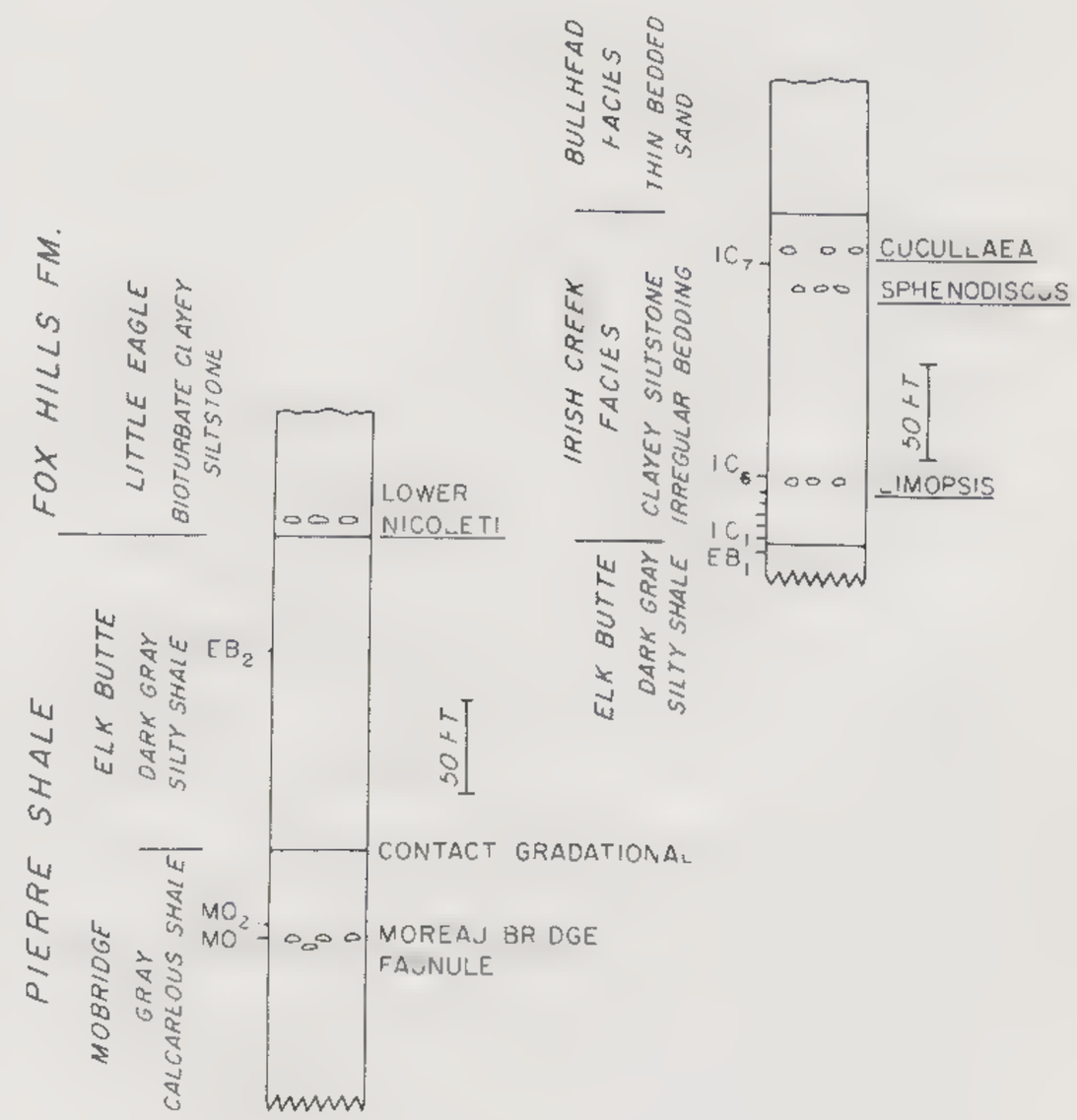


Fig. 8
Columnar sections of Upper Pierre Shale and Fox Hills Formation in Type Area. Sampling levels indicated. Section after Waage (1968).

The Elk Butte Member was sampled at two localities also: along Highway 63 where the shale underlies the Little Eagle lithofacies and westward in the Moreau Valley where it underlies the Irish Creek lithofacies. Both exposures were in the uppermost Elk Butte, as shown in Figure 8.

Sampling of the Trail City Member was carried out at several localities in order to include both lithofacies. In all cases samples were located within the section by position in the sequence of concentration layers described by Waage (1968). Location of samples of the Irish Creek and Little Eagle lithofacies is shown in Figures 8 and 9.

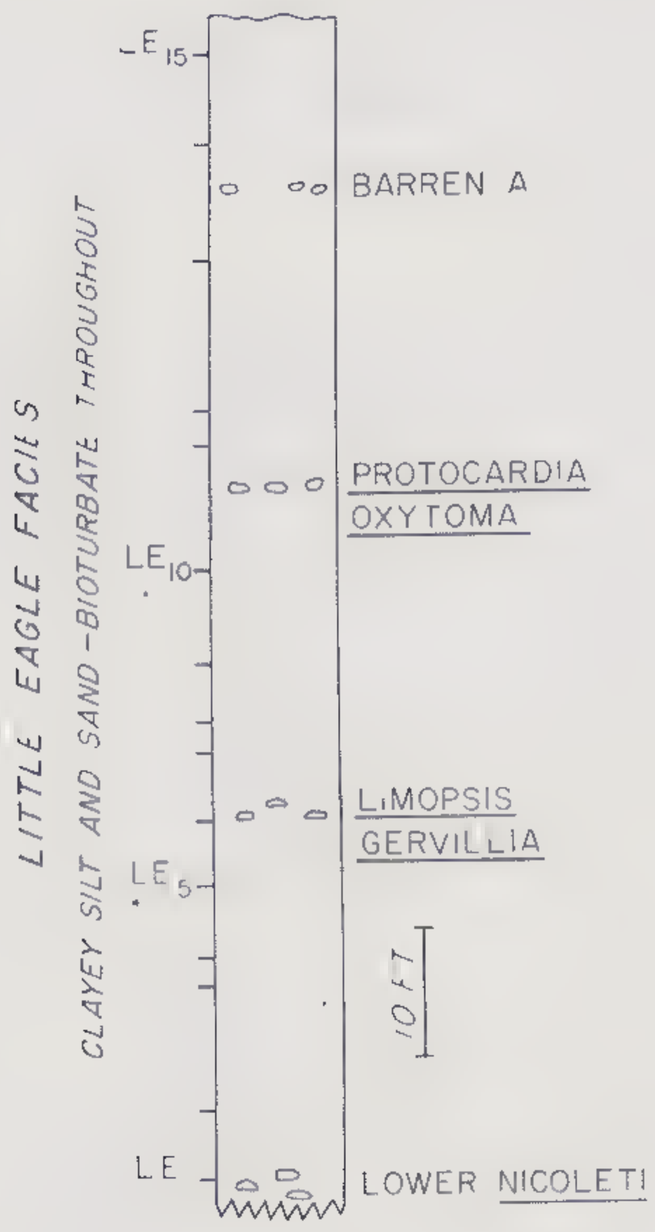


Fig. 9
Columnar section of Little Eagle facies with sampling levels indicated (measured section from Waage, 1968).

The Upper Fox Hills is characterized by large amounts of sand. This, plus spectacular lamination, cross-bedding, and slump structure, indicates a high-energy, very nearshore environment. No systematic collections were made of this facies, but a few samples were taken of the well-laminated sand and silt of the Bullhead facies, in order to examine the sedimentary structures.

Lithology and Sedimentary Structures

Uppermost Niobrara and Niobrara-Gammon Contact In the Red Bird area, the top of the Niobrara is a light brown, calcareous claystone. White, round particles the size of fine sand occur throughout the rock matrix; they are calcareous and similar to the coccolith aggregates observed by Dunham (1961).

Little gross structure is apparent in the Niobrara samples. Microscopically, the rock is uniform as well; the only structure is a planar lineation produced by the alignment of fine carbonaceous flakes parallel to each other and to the bedding (Fig. 18). The coccolith aggregates also form discontinuous linear, horizontal bands. However, true laminae are not present, only lenslike bands of darker and lighter brown matrix. The lighter matrix is more reactive to dilute HCl and presumably has a higher percentage of carbonate than the dark lenses.

There is no sign of any burrowing structures in the samples, and the planar fabric implies a lack of mixing: the primary horizontal arrangement of platy particles produced during deposition remains a feature of the rock.

The contact with the overlying Gammon Member is quite sharp, the brown, calcareous claystone changing to a dark, noncalcareous claystone.

Gammon Member The Gammon is a uniform claystone throughout, with occasional red-weathering ironstone concretions. It becomes progressively darker upwards. Internally, the rock is a dark gray, clay groundmass with thin bands of fine silt which act as planes of fissility. The fine carbonaceous flakes present in the Niobrara are more common in the Gammon, and are parallel and horizontal here also. Again there are no burrow structures present. Nor are there any inorganic sedimentary structures other than the fabric parallelism, which improves upward as the black flakes become more concentrated within the matrix, and the amount of silt drops.

The Gammon Member in the Chadron area is nearly identical in lithology, and a similar upward stratigraphic gradient of finer grain size, darker color, and more concentrated planar flakes is present (see Fig. 18).

Sharon Springs Member At Red Bird, the Sharon Springs is a nearly pure claystone. Laterally persistent bentonites are abundant, but no other megascopic change in lithology is visible. The rock is hard and brittle, breaking easily into thin chips which are themselves fissile. The shale weathers into papery flakes which actually form small dunes on the flatter parts of the outcrop.

Internally, the rock displays little structure. There is a large amount of the black carbonaceous flaky material found in the underlying members. In the Sharon Springs its aspect is similar to the flaky carbonaceous matter described by Zangerl and Richardson (1963) in black shale from the Mid-Continent Pennsylvanian. This similarity, plus the high content of organic carbon (5.2%, Fig. 10), suggests that the flakes in the Pierre are finely comminuted organic material. The flakes are much more concentrated than in the underlying Gammon, and more perfectly planar and parallel, as can be seen in Figure 18. Few laminae are present in the Sharon Springs; the distribution of black flakes is uniform both vertically and laterally and nowhere is the fabric disturbed; no burrows are found. Occasionally there are thin stringers of fine silt, which are laterally continuous over a distance of centimeters; above the level of Sample SS_9 these silt layers become more common.

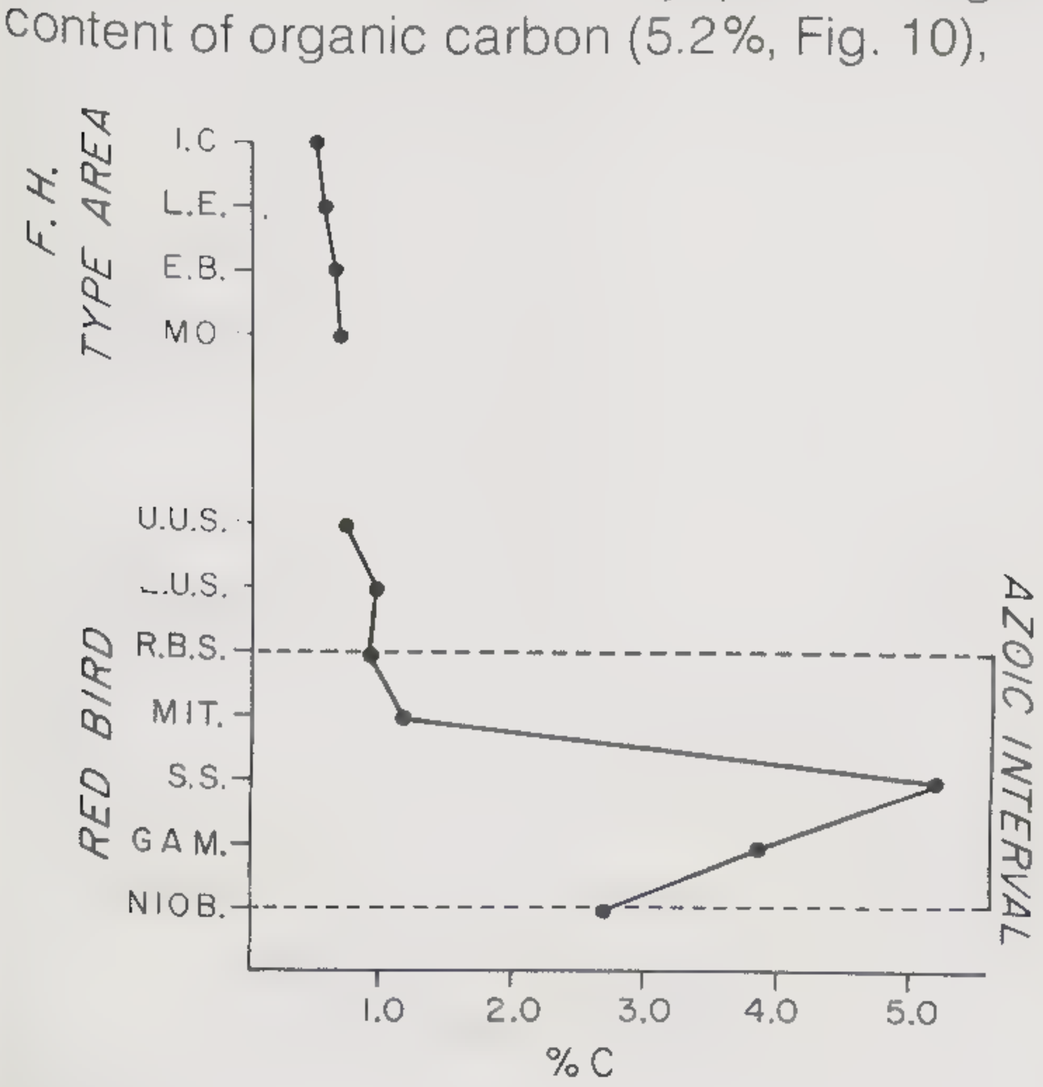


Fig. 10
Organic carbon content of shale samples from Red Bird and Type Fox Hills Area. Values are weight percent carbon from carbonate-free shale samples. Abbreviations: I. C. = Irish Creek; L. E. = Little Eagle; E.B. = Elk Butte; MO. = Mobridge; U.U.S. = Upper Unnamed Shale; L.U.S. = Lower Unnamed Shale; R. B. S. = Red Bird Silt; MIT. = Mitten, S. S. = Sharon Springs; GAM. = Gammon; NIOB. = Niobrara.

At Chadron, the Sharon Springs is identical, a very dark claystone with a horizontal internal fabric. The increase in silt near the top of the Member occurs here also. No biogenic structures are present.

Mitten Member The Mitten is a softer, lighter gray, and less fissile shale than the Sharon Springs. There is considerable fine silt in the clay groundmass, generally scattered, rather than in discrete lenses or laminae. The parallel black flakes of the Sharon Springs are lacking; the Mitten flakes are smaller and more irregular in shape and show no preferred orientation. As a result, there is no primary horizontality present in the rock fabric; it is nearly homogeneous. In the lower Mitten no true biogenic structures were observed, but in the topmost part of the Member, there are tiny, dark burrows present, which are nearly circular in cross-section, with diameters of 0.1 to 0.5 mm. Mitten lithology and burrows are shown in Figure 19.

Red Bird Silty Member The Silty Member is a light brown clayey siltstone, blocky rather than fissile, with abundant biogenic structures. Fragments of layers of light silt or dark silty clay remain within the predominantly clayey silt matrix. There is no other lamination present. On the other hand, burrows are abundant; they are similar to those of the Mitten, but larger and better defined, some displaying small halos of silt around the central dark clay zone (see Fig. 19).

Lower Unnamed Shale Member The Lower Shale overlies the Silty Member conformably; the contact is a zone several feet thick in which the silt content drops sharply and the rock changes back to dark gray. The Lower Shale is a silty claystone; in its upper parts fine stringers of coarse silt occur, but these are the only physical sedimentary structures. The rock is blocky and not fissile.

Burrows are abundant in all samples of the Lower Shale. They are the same dark, subhorizontally aligned, circular type, but they are smaller than those of the Silty Member, as can be seen in Figure 19.

Upper Unnamed Shale Member and Fox Hills Formation The Upper Shale is a light grayish-brown, clayey siltstone similar to the Silty Member. Upward, stringers of coarse silt and fine sand begin to appear and finally predominate; the rock is a coarse siltstone at the Fox Hills contact.

A clear gradient in sedimentary structures is present in the Upper Shale and basal Fox Hills (Fig. 19). The lower samples are completely dominated by biogenic structures, and the rock is a nearly homogeneous clayey silt, with no trace of bedding. Well-defined burrows, filled with dark clay or light silt, are very abundant and large. Upward, there are stringers of coarse silt and fine sand, more or less continuous through the clayey silt groundmass. Although the silt laminae are found only at certain levels high in the Upper Shale and basal Fox Hills, the sediments become steadily coarser upward, finally changing to coarse, cross-laminated silts just below the large cross-bedded sandstone of the Fox Hills Formation. No biogenic structures are present; physical structure predominates entirely.

Mobridge Member The Upper Mobridge is a gray silty claystone. Megascopically, the only structures are horizontal bands of white particles the size of fine sand. They dissolve in dilute HCl and outwardly resemble the coccolith aggregates mentioned above. Microscopic examination shows that the rock fabric is composed of uniform silty clay. The black flakes characteristic of the Pierre at Red Bird are also present here, and again they are aligned horizontally and subparallel; burrows of any kind are very rare, however, and the fabric does not have the mixed aspect of the Upper Pierre at Red Bird.

Elk Butte Member The Elk Butte is a silty clay, with very thin, discontinuous stringers of light silt, which become thicker and more common upward in the Member. Sample EB_2 (Fig. 20) from 60 feet below the Fox Hills, shows numerous small, dark burrows which are not well defined; that is, the burrow grades into the groundmass without a sharp contact or an aureole. The rock is a mixture of fine layering and homogeneous fabric; parts of the silt stringers are laminated and continuous laterally, and other parts are simply mottles of light silt in the gray groundmass.

Fox Hills Formation—Irish Creek Lithofacies A sharp increase in silt content over an interval of a meter or two marks the Elk Butte-Irish Creek contact. Silt becomes coarser and more abundant upward within the Irish Creek, becoming localized in irregular layers in a silty clay groundmass. This irregular layering is the characteristic appearance of the facies; however, near the top of the Member, it gives way to a more homogeneous mixture of coarse, silty clay, without true layering. And even where the silt layers are clearly laminated, they are not laterally continuous for more than a few centimeters; they are often broken and mottled into the matrix, as is shown in Figure 20.

Fox Hills Formation—Little Eagle Lithofacies Throughout, the Little Eagle is a gray-brown, clayey siltstone. Near the top, broken stringers and mottles of fine sand appear. In all the samples, burrows of various types are abundant. The small dark burrows are larger (over 2 mm in diameter) than in the Mobridge and Elk Butte, and are better defined. Commonly they have a halo of light silt around a dark clay central area. In addition, larger burrows filled with light silt are common.

The rock fabric is almost completely mottled; occasional fragments of laminated layers of silt and clay occur in a few samples, but otherwise there is no stratification. Mottling and the various burrow types are shown in Figure 20.

3. Biogenic Structures

Burrow Morphology

Although very little work has been done on infaunal burrow structures in rocks, investigations of modern sediments have shed light on the processes of burrowing, and these insights can be applied to the sedimentary record. In particular, the burrows in Recent sediments figured by Rhoads (1970) are similar in size and shape to structures in ancient mudstones. The Recent burrows are produced by the horizontal movement of deposit-feeding protobranchs, polychaetes, nematodes, and holothurians, generally within the upper few centimeters of the sediment, and burrows in ancient rocks are ascribed to the same taxa although no body fossils prove this origin.

Similar burrow shapes occur in the Devonian Sonyea and in the Cretaceous Pierre and Fox Hills. As noted above, in the lithologic descriptions, the most common burrow form is a small, dark, clay-filled, horizontal structure. These burrows are nearly circular when viewed in cross-section, and elongate cylinders in longitudinal section, as is shown in Figure 21. There is rarely any internal structure to be seen, but the filling contrasts with the silty clay of the surrounding matrix; the filling is a well-sorted clay in most cases. Occasionally, backfilling structure can be observed in dark burrows, as can be seen in Figure 21, *E*. The definition of the burrow edge varies; in claystones such as the Mitten or the Elk Butte, the dark burrow grades into a groundmass that is only slightly lighter, and definition is poor. However, in a siltier rock such as the Little Eagle, the dark burrows are sharply delineated against the more poorly-sorted, lighter, clayey silt.

Some of the samples of these clayey silts contain burrows with actual halos of clean silt surrounding the darker central zone. Halos are circular around the dark burrows in cross-section, and they cut across the primary lamination of the rock. They are therefore considered to be true effects of the burrowing process. Examples of halos are shown in Figure 21, A. Halos are common in rocks of high silt content, suggesting that the deposit-feeding, vermiform animal exercised a size selection, ingesting clay and rejecting the larger silt grains in its path. Fecal material expelled by the animal would be clay-sized and would be surrounded by the zone of rejected and displaced silt particles. The entire burrow, then, consists of two concentric cylinders: a dark, clayey inner one, and a light, silty outer one, the whole complex cutting across the preexisting structure of the sediment. (These burrows are shown diagrammatically in Figure 11.)

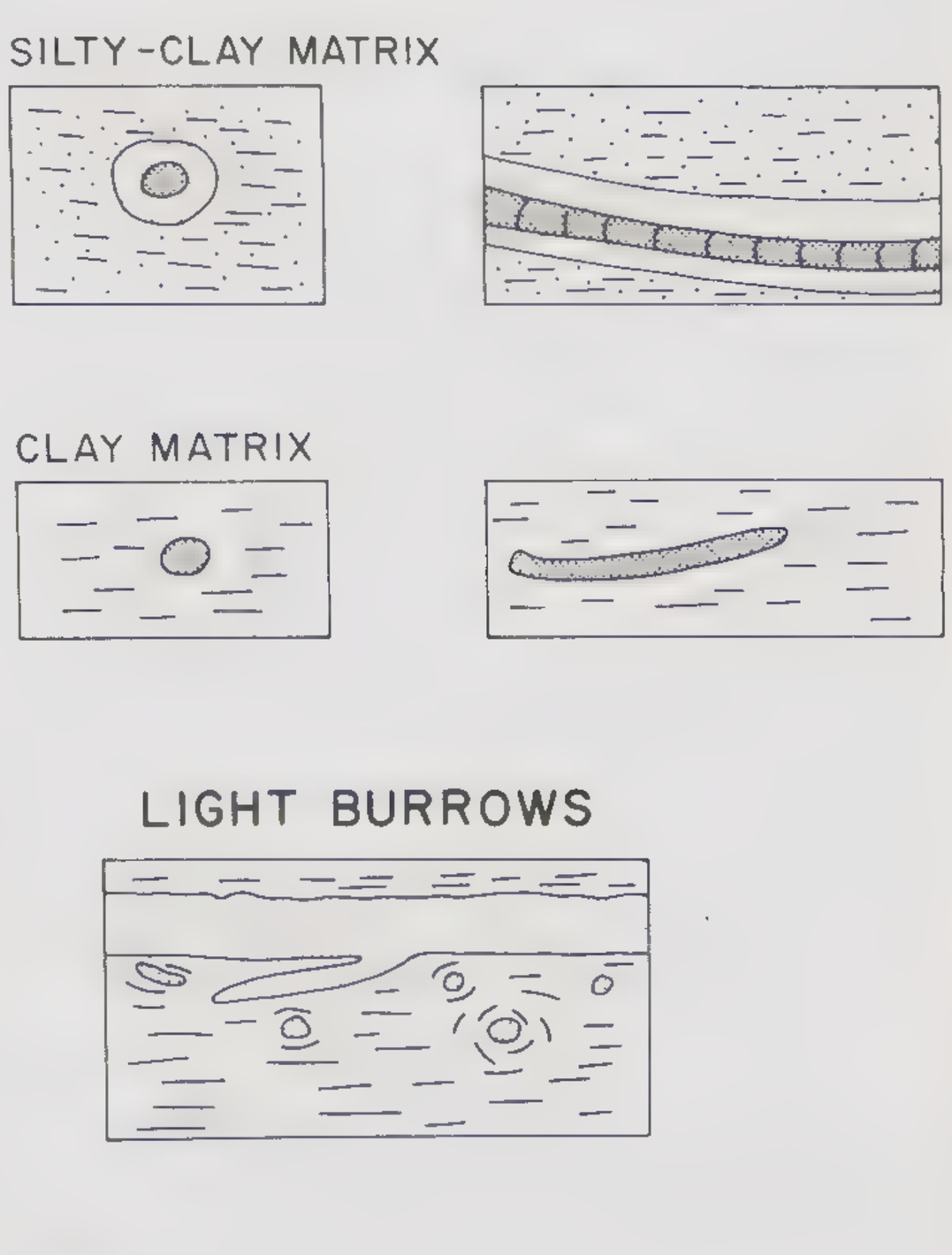


Fig. 11
Major burrow forms in shale and mudstone.

The second major burrow type is lighter in color than the surrounding matrix. These burrows are filled with silt rather than clay and are usually larger than the dark forms. Light burrows are circular in cross-section and do not seem to possess halos. Pressure annuli are visible around some light burrows, however, apparently produced by the animal's movement through a plastic sediment (see Rhoads, 1970). The silt filling of light burrows is better sorted than the general clayey silt lithology of the whole rock.

The silt fillings of light burrows are structureless. Whereas the dark burrows appear to be back-filled by deposit-feeding animals, the light burrows are probably simple mechanical infillings of voids produced by animals pushing through the sediment. There is no evidence of particle rejection in the form of a halo of disturbed grains around a central burrow. Instead, the surrounding matrix may be squeezed into pressure annuli, particles aligned with their long axes tangent to the burrow circle. In addition, light burrows are common only in siltstones or in claystones with interlaminated silt layers; light burrows will be seen only within the silt layers, or extending from them into the clay. It would seem that light burrows are produced by silt filling the opening left by a burrower pushing the sediment aside, rather than ingesting his way through it. Typical light burrow structure is seen in Figure 21 and is diagrammed in Figure 11. This type of burrowing process mottles the silt into the clay; when burrowing is beginning, the sediment will have a marbled appearance (mottled facies) and the burrows will be clearly outlined. With increasing bioturbation, the sediment will approach homogeneity, burrow fill will include more of the original matrix, and the burrow will tend to grade into its surroundings (homogeneous facies). Burrows in homogeneous sediments are also ill-defined because of the higher water content of reworked mud and the prevalence of thixotropic, rather than plastic, deformation of the matrix surrounding the burrow (Rhoads, 1970).

Bioturbation Trends

Dark burrows range in size from approximately 0.1 to 2.0 mm in diameter, a minimum and maximum which is identical in both the Devonian and Cretaceous rocks. Also, the sizes characteristic of given lithologies show parallel trends in the Sonyea and Pierre-Fox Hills sequences. With size increase go increases in diversity of size, in diversity of burrow type, and in absolute number of burrows.

In the Sonyea, only the Chenango Region shales contain burrows. Near the western edge of the Region, in very finely silty claystones, only dark burrows are present, if bioturbation exists at all.

Eastward, in siltier claystones, the dark burrows are large, in the 1–2 mm range. Small sizes are present as well, however, and light, silt-filled burrows make their appearance also. Light burrows are always large, 1–2 mm in diameter. In these eastern clayey silts (Localities 7, 11, 12, 18, 20, 23) burrows are quite abundant, and while parts of the depositional lamination can still be seen in the western Chenango region, the fabric tends toward a complete bioturbate eastward.

A similar gradient is obtained from the Cretaceous sequence. The basal black shales lack burrows entirely, and while bioturbation occurs in the upper Mitten Member, burrow sizes are very small. In the similar dark silty claystones of the Lower Shale there is still only one burrow type present, the small (1.0 mm diameter maximum) dark form.

In contrast, the clayey silts of the Red Bird and Upper Shale Members contain dark burrows of various sizes, up to 1.5 mm. In the Upper Shale especially, these burrows are haloed with silt, and large light burrows are common. Bioturbation is nearly total throughout the Red Bird and Lower Shale Members and in the basal Upper Shale; burrow sizes are larger in the siltier Members, however, and the most diverse, most populous, and largest infauna was present in the Upper Shale.

The Type Fox Hills Area displays a similar pattern. The Mobridge Member is without infaunal traces, small dark burrows first appearing in the Elk Butte. Full burrow abundance and diversity is found only in the overlying Fox Hills, in both the Little Eagle and Irish Creek facies. These sediments are nearly identical with those of the basal Upper Shale at Red Bird; a very prolific, diverse and large-sized infauna inhabited these muds.

Basically, there are three vertical gradients visible in the Cretaceous sections. The first ranges from the basal black shales at Red Bird up through the bioturbate Red Bird Silty Member; burrows increase in size, diversity, and abundance upward. The Lower Shale marks a return to Mitten-type conditions, and then the increasing bioturbation from the Lower Shale into the Upper Shale defines the second gradient. The third sequence includes the laminated Mobridge, the dark-burrowed Elk Butte, and the totally bioturbate Trail City, in the Type Fox Hills Area. Each stratigraphic gradient is characterized by increasing alteration of the sediment as well as increasing body size and diversity of the infauna itself.

These trends in abundance, size, and diversity fit well with the effects of a marine oxygen gradient as discussed above, and the facies changes in both the Devonian and Cretaceous rocks are interpreted as resulting from oxygen gradients in the original depositional environments.

4. Paleoenvironments

In a hypothetical silled basin, the deep anoxic zones represent Schäfer's Lethal Isostrate, Biofacies 5; animals and their burrows are lacking. Toward the basin margin, in shallower water, anoxic bottom conditions should give way to better oxygenation, and, other factors being equal, benthic life should become established, beginning with those organisms most tolerant of dysaerobic conditions: polychaetes, aschelminths, and other minor worm phyla, and possibly protobranch bivalves. Further increases in oxygenation should increase the benthos in terms of diversity, body size, and total biomass; the result of such a complete colonization of the bottom is a strongly bioturbate fabric. This area is Schäfer's Biofacies 4, Vital Isostrate.

With still further shallowing, physical structures will appear, at first broken and mottled by biogenic activity, but increasingly persistent as the shoreline is approached. This zone would correspond to Schäfer's Biofacies 2, Vital Heterostrate. The sea floor here is feeling the effects of surface phenomena occasionally, reworking or rapid deposition during major storms or tidal seiches, for example; but the benthos is generally able to maintain itself and to partly destroy the physically-produced structures.

Finally, in the nearest-shore zone, physical forces predominate and swamp out the benthos. Biofacies 3, the Lethal Heterostrate, with its very unstable substratum, is too harsh an environment for most infaunal benthos. Again, benthic fossils and biogenic structures will be absent.

The same sequence in lateral facies change found in traversing a basin from deep to margin should present itself in vertical section when a basin is filled in. In both cases what is involved is a gradient in environments of the sequence Schäfer Biofacies 5, 4, 2, 3 as the water depth diminishes. Absolute depth will be highly variable, depending on sill depth, general climate and amount of runoff, fetch and wave-mixing depth, and tidal activity. The general sequence should be observed, however, and some estimates of depths of the various facies in ancient seas can be made by analogy with the Recent.

Sonyea Group

Lake Erie Region

The actual depth of the Upper Devonian basin is uncertain. The bottom was below wave base; in fact it was probably much deeper, lying below the zone of surface mixing (oxygenated water), and under a stratified

water column that assured stagnation. A Recent example of a restricted sea, the Black Sea, is mixed by surface motion and vertical thermal currents to depths of nearly 200 m. Wave-mixing depth is shallower in local anaerobic basins like Saanich Inlet, due to much smaller waves formed in a limited fetch distance. Mixing depth varies when strong temperature differentials are present seasonally; for Saanich Inlet, the winter mixing lowers the oxgenated zone to 150 m, whereas the summer thermocline raises it to 70m(Gucluer and Gross, 1964).

In addition to the amount of surface mixing, the general climate and sill depth control the basin hydrography. Unfortunately, the sill depth and hydrographic conditions of the Devonian basin are unknown, although the lateral extent of the Upper Devonian black shales indicates a large sea was present. Isochronous shale tongues are clearly correlatable from central New York State to Lake Erie, and probably beyond, to the Upper Devonian-Lower Mississippian black shales of the Mid-Continent, the Cleveland, Chattanooga, and Grassy Creek Shales and their local equivalents (Cooper, et al, 1942). The New York shales indicate a basin at least 200 miles wide. If the Midwest black shales are lateral equivalents, the outcrop belt is over 1000 miles across.

In any event, a large Upper Devonian basin is indicated, with plenty of area for full-sized marine waves and surface mixing. Strong waves and storm events are also indicated by the numerous erosional coquinites in the shelf depth rocks of the Sonyea Group. In short, the Devonian sea was no millpond. By analogy with Recent seas, surface waves probably reworked the bottom sediments to depths of 20–40 m, and the well-oxygenated mixed layer extended much deeper, to 150–200 m. The Middlesex of the Lake Erie Region was certainly deposited below the mixed layer of the Devonian sea; thus the minimum value for depth in this part of the sea was probably about 150 m.

Finger Lakes Region

Middlesex black shales in the Finger Lakes Region are similar to those of the Lake Erie Region; again there is no trace of biogenic structure in the rock.

The silt beds are thin and closely interbedded with shale layers. Internally, the gentle cross-laminated grading upward into horizontal lamination, and an upward decrease in grain size which merges into the next overlying laminated shale, suggests turbidite sedimentation. According to Bouma's (1962) model of the ideal turbidite, these thin silt layers would constitute the distal portions of turbidite flow; the coarse basal layers, with attendant basal erosion, are lacking in the Middlesex of the Finger Lakes Region.

Farther east, in the Ithaca area, the Montour and Sawmill Creek Shales are interbedded with thick silt beds with sole marks. These silt layers seem to represent repeated small turbidity current flows, the distal edges of which appear as the thinner fine silt layers in the Middlesex of the Finger Lakes Region.

Large, complete-sequence turbidites (see Bouma, 1962; Walker and Sutton, 1967) appear in the Sonyea as well. Higher in the section, and correlating eastward with the massive delta buildout in the Glen Aubrey Formation, and westward with the best-laminated Middlesex (Fig. 17, *D*), the Rock Stream Member crops out from Ithaca westward through the Finger Lakes. The thick beds of sand and silt in the Rock Stream were interpreted by Walker and Sutton as turbidites flowing westward from a shelf edge near Ithaca into the Upper Devonian basin. During intervals of black shale deposition represented by the Montour and Sawmill Creek tongues, sediment delivered to the shelf edge was quantitatively much less than during deltaic phases; large turbidity flows were lacking, but small flows probably formed the thin, repetitive silts interbedded with the Finger Lakes black shales.

Since turbidites represent slope and marginal basin floor sedimentation, the Finger Lakes

Region was probably somewhat shallower than seafloor in the Lake Erie Region, but still below mixing depth.

Chenango Region

The westernmost exposures of the separate shale tongues are slightly east of Ithaca; the shales are not clearly differentiated from the intervening beds in this area, being merely darker zones in a sequence of interbedded dark claystones and thick silt layers. Both the Montour (Locality 15) and the Sawmill Creek (Locality 25) Shales are lithologically similar to the Middlesex to the west: black, pyritiferous, perfectly laminated claystone. The intervening beds between the shale horizons are sparsely fossiliferous dark-gray shales and siltstones ("open shelf environment" of Sutton, Bowen, and McAlester, 1970). Apparently this region was marginally inhabitable during times of deltaic buildout but became azoic during deposition of the black shale tongues.

Change from purely open shelf sedimentation to Triangle prodelta facies takes place a few miles east of Locality 30. At Locality 29 the black shales begin to be better defined in relation to the intervening beds. Triangle prodelta sediments are locally fossiliferous and clearly contained an abundant infaunal population. Figure 22, *C* shows dark mudstone from the Triangle beds at Locality 29; burrows are abundant and diverse in size and type, and no trace of primary lamination remains. The facies is Vital Isostrate, indicating oxygenated water below normal wave base.

However, upward in the section, toward the Sawmill Creek horizon, burrow diversity, size, and number drop, as seen in Figure 22, *B*, producing a laminated silty claystone slightly disturbed by biogenic structures. Farther upward, at the Sawmill Creek proper, no biogenic structures are encountered (Fig. 22,*A*). The facies has returned to Lethal Isostrate. At this locality then, conditions were favorable for benthic life during deltaic phases, but hostile during black shale phases.

Referring back to the basin model of biofacies change, Lethal Isostrate conditions would indicate deeper water, with the sea bottom in a stagnant water zone. The upward facies change from Vital to Lethal Isostrate indicates relative sinking of the shelf down into the stagnant water, a transgression, and a shifting of the Lethal Isostrate environment shoreward. Of course the other environments would be shifted as well, so that within a shale tongue there should be found facies anomalously far eastward of their positions during a deltaic buildout, as shown diagrammatically in Figure 12. This pattern is what is found: both shale

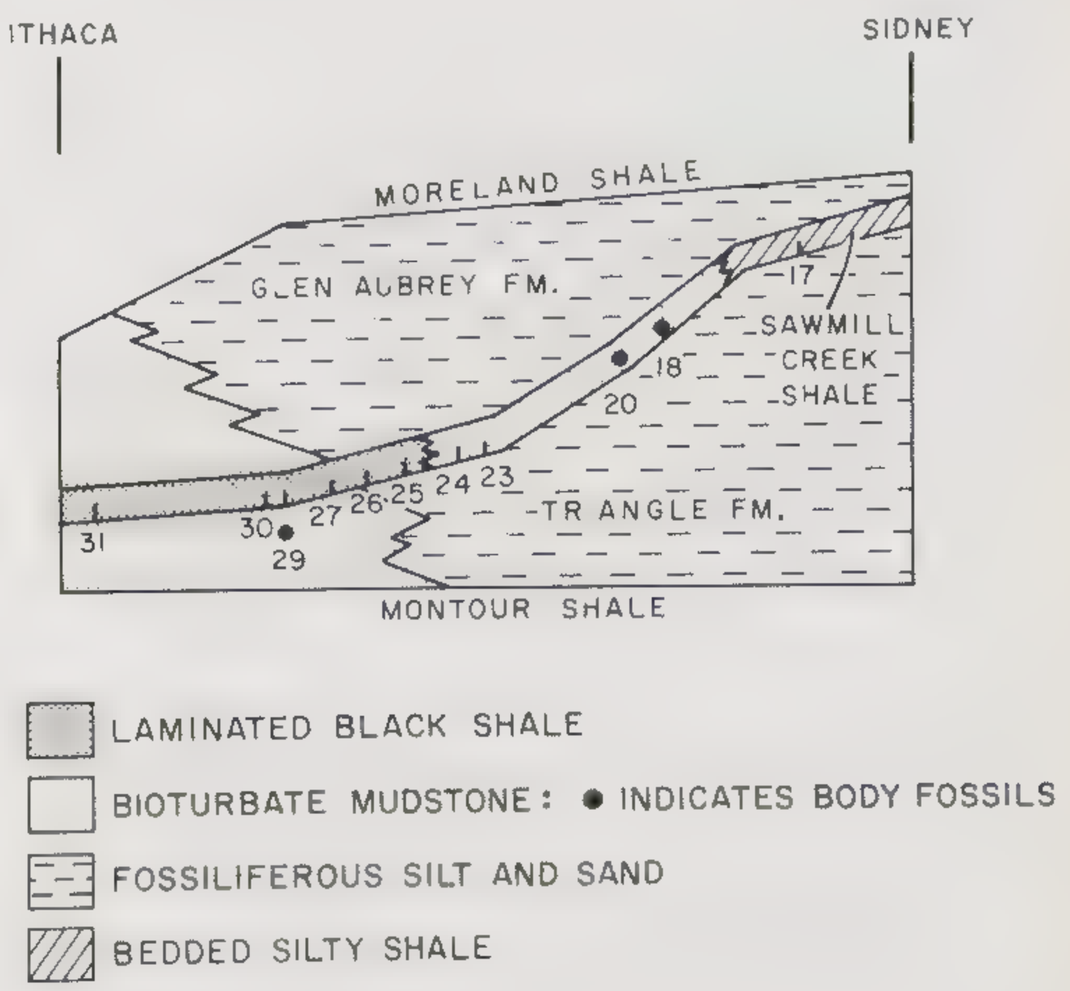


Fig. 12
Eastward shift of facies in Sawmill Creek Shale relative to the deltaic episode of the Triangle Formation. Shift was produced by Sawmill Creek transgression.

tongues change facies laterally, becoming increasingly silty and less well laminated and changing assemblages of biogenic structures. The eastern part of the Chenango Region contains shales similar to the distal prodelta facies of the Triangle wedge (cf. rock from Locality 20 and Locality 29 in Fig. 22, D and E). The facies is identical—occasional body fossils in a completely bioturbated mudstone, with diverse burrow shapes and sizes. In essence, depositional environments have been shifted shoreward by a distance of over 30 miles. If modern shelves are a guide (average gradient of 1:1000), the transgres-

sion involved a relative submergence of more than 50 m.

At intervening black shale localities in the Chenango Region, there is a west-to-east gradient of increasingly large and diverse biogenic structures reflecting increasing oxygenation (see Fig. 22).

Sidney Region

The very thin outcrops of black shale in the easternmost localities (strandline area) interbed with thick gray sands and silts, and shale overlying silt beds has a cross-laminated basal contact indicating that the current action that produced the silt layer persisted during the deposition of the clay in an environment of variable current energy. This contrasts with the silt-shale contacts in the Finger Lakes Region where the change to clay sedimentation is accomplished in horizontal laminae; here the current event which produced the silt bed was completely separated temporally from the onset of clay sedimentation.

The Sidney Region shales represent the eastward margin of marine transgression, and the close proximity of beach sands below and red mudstone above indicates a shallow environment. The sediments, dominated by evidence of current activity, were deposited in Biofacies 2 and 3, Vital Heterostrate and Lethal Heterostrate.

The overall conditions of deposition within the Sonyea basin during periods of deltaic progradation and during transgression are diagrammed in Figure 13.

Pierre-Fox Hills

The same general sequence of lithofacies, from laminated black shales to bioturbate mudstones, occurs in the Pierre Shale and Lower Fox Hills. There are differences from the Upper Devonian basin, however; turbidites are absent in the Cretaceous section, and the thickness of deltaic sands and silts is much less than in the Sonyea Group.

In addition, the Cretaceous shales are not so well laminated as the western Sonyea rocks. The Sharon Springs is fissile, with a highly parallel and horizontal fabric, but without laminae. This indicates greater uniformity of depostion, a lack of the regular (perhaps annual) sedimentation events that characterize the Middlesex Shale.

However, the Cretaceous basin was deep enough to develop a stratified water column. The black shales at the base of the Pierre are excellent examples of the Lethal Isostrate biofacies.

In addition, the uppermost Niobrara lacks biogenic structures; the calcareous shale is formed of coccoliths and clay, wholly pelagic sediment sources for a stagnant bottom. Gammon lithology could then be produced by elimination of the biogenic sedimentary component.

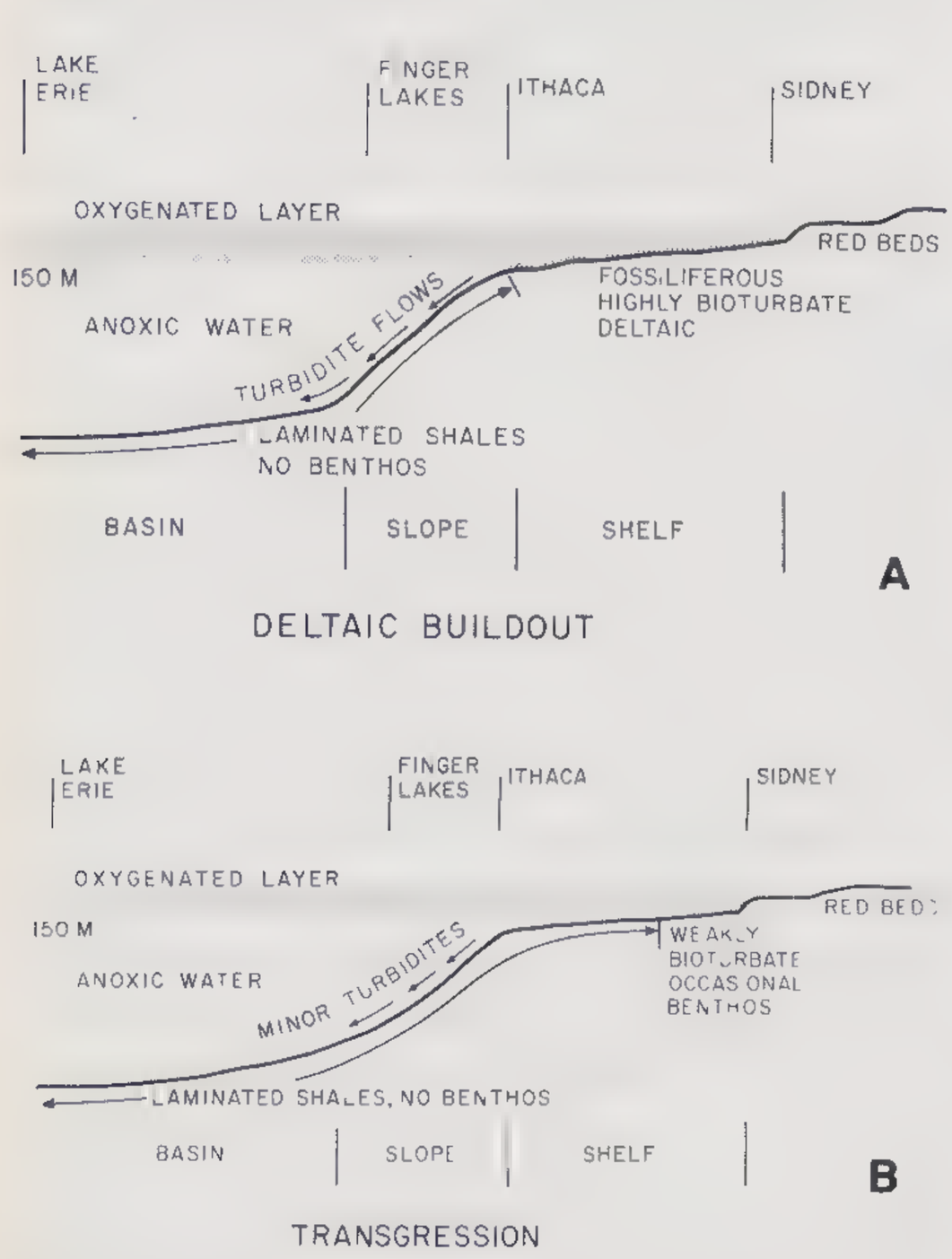


Fig. 13
Conditions of deposition for the Sonyea Group: A) during periods of deltaic progradation which produced the Triangle and Glen Aubrey lobes, and B) during transgressions which produced the Montour and Sawmill Creek Shale tongues.

The Gammon becomes progressively darker and more fissile upward. Maximum blackness and fissility are reached in the Sharon Springs, marking the period of greatest stagnation of the bottom water. The combined Gammon and Sharon Springs are the lithologic equivalent of the western shales of the Sonyea Group (Lake Erie and Finger Lakes Regions).

The Mitten was clearly inhabited by infaunal benthos; the rock fabric is mixed and mottled, but burrows are uniformly small and ill-defined. Bottom conditions were probably marginally aerobic only.

Fully aerobic conditions are reached in the Red Bird Silty Member; here infaunal burrows are diverse in size and shape. This facies is the Vital Isostrate of Schäfer, since there is no trace of erosion or physical reworking of the sediment. The Silty Member is the lithologic equivalent of the bioturbate mudstones of the Chenango Region black shales.

A return to deeper water is indicated by the lithology of the Lower Shale, a dark gray silty claystone. Again, as in the Mitten, burrows are reduced in size and diversity, indicating marginal conditions for benthos.

Shallowing proceeded rapidly during the deposition of the Upper Shale, as evidenced by increasing grain size and the ratio of physical to biogenic sedimentary structures. The basal Upper Shale is a return to the clayey silt lithology and abundant, diverse burrow forms which characterize the Silty Member. The sediment is totally bioturbate, indicating deposition in well-oxygenated waters below wave base.

Proceeding upsection the rock is siltier and irregular layers of coarse silt and fine sand begin to appear; although biogenic structures are still very common, the infauna was unable to rework the entire sediment bulk. Clearly, the rate of sedimentation has increased; this is Schäfer's Vital Heterostrate biofaces. Finally, in the basal Fox Hills, physical reworking completely dominates; the rock is laminated and cross-laminated fine sand. The total lack of biogenic structures marks the second azoic environment, the Lethal Heterostrate. The depositional environment was very shallow by this time, well above wave base.

The Upper Pierre and Lower Fox Hills in the Fox Hills Type Area display the same sequence of environments seen at Red Bird.

Mobridge lithology is apparently unaffected by infaunal burrowers although the fabric is not so clearly laminated as the true black shales, such as the Sharon Springs.

The Elk Butte is very similar to the Lower Unnamed Shale; it is dark, silty claystone with abundant small dark burrows. Diversity is low, and epifauna are absent. Clearly it was a marginal environment for benthic life, equivalent to shales in the western part of the Chenango Region.

The Little Eagle facies of the Lower Fox Hills is the equivalent in lithology and sedimentary structure to the Upper Shale at Red Bird. In the environment of deposition, the water was well-oxygenated but below wave base.

The lateral equivalent, Irish Creek lithofacies, possesses abundant irregular layers. Biogenic structures are present, and to some extent have destroyed the physical layering; the situation is similar to the middle and upper parts of the Upper Shale at Red Bird. Shallower water, above wave base, and a higher rate of deposition are indicated for the Irish Creek as opposed to the Little Eagle. In terms of Schäfer's classification, the Little Eagle is Vital Isostrate, whereas the Irish Creek is Vital Heterostrate.

The Bullhead facies of the Upper Fox Hills is clearly Lethal Heterostrate; in most samples physical structures are entirely dominant, indicating very shallow water and a high degree of physical stress, probably an overwhelming sedimentation rate, on the evidence of the great lateral continuity of bedding.

In general, conditions in the Upper Creta-

ceous sea were somewhat different from those in the Sonyea basin. It would seem that the Red Bird area was in the deepest part of a large, semirestricted seaway and that the basal black shales represent anaerobic bottom conditions at this depth. Continued sedimentation filled in the basin, gradually eliminating the anaerobic zone. While the Upper Devonian azoic basin was a persistent feature that intermittently affected shelf environments, the Cretaceous basin during Pierre-Fox Hills deposition was azoic only during one episode, the Gammon-Sharon Springs interval, and only in the central and eastern basin, far from the major sediment sources to the west.

Water depths during the black shale interval are conjectural; the lack of both turbidites and the very perfect lamination seen in the Sonyea indicates shallower depths for the Cretaceous environment, as does the presence of rapidly prograding clastic tongues (see Pike, 1947). But certainly the shales were deposited below the mixed layer and far below the depths affected by surface waves; in fact, no trace of physical sedimentary structures other than parallel laminae is seen until near the very top of the Pierre.

The widespread continuity of the basal azoic shales points to a uniform anaerobic zone across the seaway, rather than a series of small anoxic holes. Modern-day mixing depths for large basins are generally about 150 m, as noted above. Whether the Cretaceous climate was so strongly seasonal as to cause vertical mixing on this scale is not known. However, modern seas are generally mixed to perhaps 50 m even in summer, when the water column is most stable. This is probably a minimum estimate for the depth of the Cretaceous sea during Gammon-Sharon Springs depostion, and depths of 100 m or more are likely.

Succeeding members of the Pierre were deposited at shallower depths, above the anoxic zone but below wave base, estimated at about 20 m. The Mitten and Lower Shale Members are products of the deeper part of this oxygenated zone, while the Red Bird and Upper Shale Members were laid down in the shallower part. The uppermost Upper Shale and the Fox Hills Formation alone show the physical structures indicating deposition above wave base. The suggested depths of deposition and the relationship of facies to the two regressive cycles are shown diagrammatically in Figure 14.

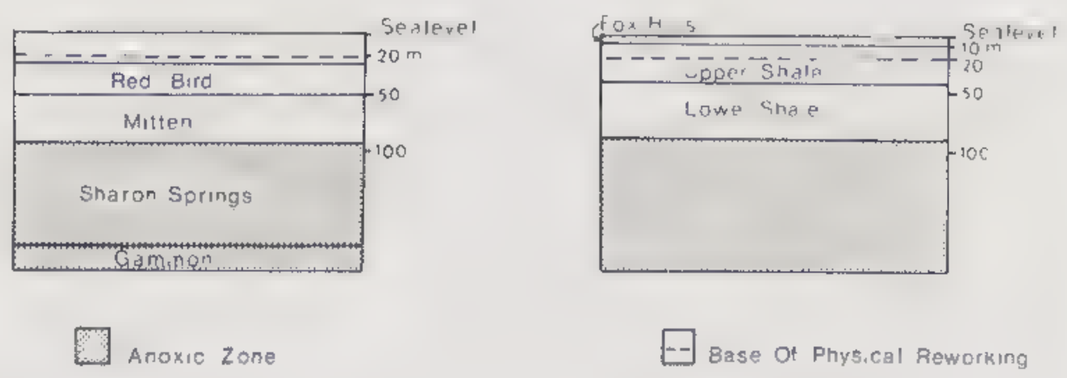


Fig. 14
A) Conditions of deposition for the Members of the Pierre Shale at Red Bird.
B) Depositional history of the Pierre Basin as inferred from biofacies changes in the Red Bird Section.

The final regressive phase is seen again in the Fox Hills Type Area. Here, physical structures produced above wave base are lacking in the Pierre and the Lower Fox Hills; only in the Upper Fox Hills did deposition take place in shallow water (< 20 m). Comparing the aspect of each facies with those at Red Bird suggests the depth limits shown in Figure 15. The maximum depth of 100 m for deposition in the Fox Hills Type Area compares favorably with two estimates based on other evidence. Mello (1969) examined the microfauna of the Mobridge Member and concluded that a maximum water depth of 60 m was implied by foram assemblages. Also, stratigraphic sections by Waage (1968) show the maximum thickness of the Lower Fox Hills Formation to be 80 m; since the uppermost beds of this

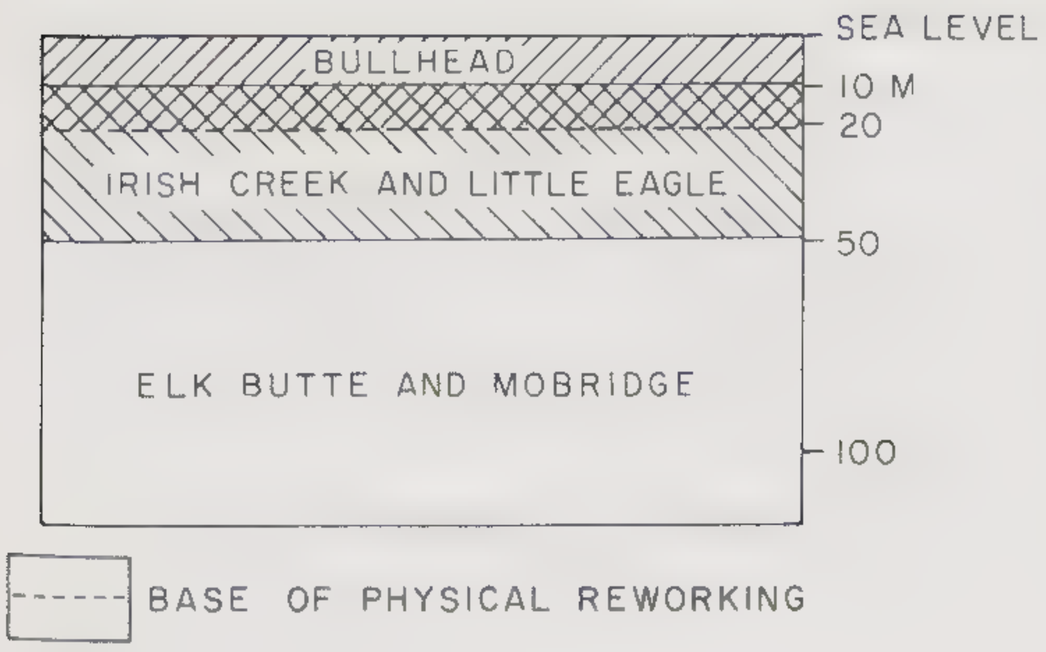


Fig. 15
Conditions of deposition for the Upper Pierre Shale and Fox Hills Formation at the Type Fox Hills Area.

interval contain the intertidal *Ophiomorpha*, 80 m is a good approximation of the water depth at the beginning of Fox Hills sedimentation.

5. Summary

During Late Devonian time a persistent deep anoxic basin was present in western New York State. On the basin floor pelagic sedimentation produced finely-laminated clays, which remained undisturbed because of the absence of benthic animals. Water depths in this basin were probably greater than 150 m.

To the east the basin floor sloped upward and the laminated clays alternated with turbidity flows coming off a shelf edge in the Ithaca area. Like the basin floor the slope lay below the oxygenated zone at the sea's surface.

On the shelf conditions alternated: during deltaic episodes (Triangle and Glen Aubrey Formations) the water was shallow, well-oxygenated, and favorable to shelled benthos; but when transgressions (Montour and Sawmill Creek Shales) increased the depth, the shelf lay at the base of the surface mixed zone, and the benthos was restricted to soft-bodied infauna tolerant of marginal oxygenation. Each transgression during the Late Devonian shifted basinal environments eastward, bringing azoic conditions onto the shelf edge and producing a barely-habitable biotope all across the shelf.

A similar anoxic basin in the Western Interior United States was filled in during the Late Cretaceous by the Pierre Shale and Fox Hills Formation. The initial Pierre sedimentation (Gammon, Sharon Springs) took place in quiet anaerobic water over 100 m deep, but as the basin filled the bottom built up through a semioxygenated zone (Mitten) to fully oxygenated surface water (Red Bird). The regressive trend was interrupted by an episode of deeper water, low-oxygen conditions (Lower Shale), but shallowing quickly resumed, and the final marine sedimentation took place in very shallow and well-oxygenated water (Upper Shale and Fox Hills Formation).

Literature Cited

Allen, J. R. L. 1964. Sedimentation in the modern delta of the River Niger, West Africa. *In* L.M.J.U. Van Straaten [ed.] Deltaic and shallow marine deposits. Elsevier, New York, p. 26–34.

—— 1965. Late Quaternary Niger Delta, and adjacent areas: sedimentary environments and lithofacies. Am. Assoc. Pet. Geol. Bull. 49: 547–600.

—— 1970. Physical processes of sedimentation. American Elsevier, New York. 248 p.

Bouma, A. H. 1962. Sedimentology of some flysch deposits. Elsevier, New York, 168 p.

Buchanan, J. Y. 1890–1891. On the occurrence of sulfur in marine muds and nodules, and its bearing on the mode of formation. Proc. R. Soc. Edinburgh 18:17–39.

Calvert, S. E. 1964. Factors affecting distribution of laminated diatomaceous sediments in Gulf of California. *In* T. H. van Andel and G. G. Shor, Jr. [eds.] Marine geology of the Gulf of California. Am. Assoc. Pet. Geol. Mem. 3, p. 311–326.

——— 1966. Origin of diatom-rich, varved sediments from the Gulf of California. J. Geol. 74: 546–565

Caspers, H. 1957. Black Sea and Sea of Azov. *In* J. W. Hedgepeth, [ed.] Treatise on marine ecology and paleoecology, v. 1, Ecology. Geol. Soc. Am. Mem. 67, p. 801–889.

Coleman, J. M. and **S. M. Gagliano.** 1965. Sedimentary structures: Mississippi River deltaic plain. *In* G. V. Middleton [ed.] Primary sedimentary struc-

tures and their hydrodynamic interpretation. Soc. Econ. Paleontol. Mineral. Spec. Publ. 12, p. 133–148.

Coleman, J. M., S. M. Gagliano, and **J. E. Webb.** 1964. Minor sedimentary structures in a prograding distributary. Mar. Geol. 1: 240–258.

Colton, G. W. and **W. deWitt.** 1958. Stratigraphy of the Sonyea Formation of Late Devonian age in Western and West-Central New York. U.S. Geol. Surv. Oil and Gas Invest. Chart OC 54.

Cooper, G. A., C. Butts, K. E. Caster, G. H. Chadwick, W. Goldring, E. M. Kindle, E. Kirk, C. W. Merriam, F. M. Swartz, P. S. Warren, A. S. Warthin and **B. Willard.** 1942. Correlation of the Devonian sedimentary formations of North America. Geol. Soc. A. Bull. 53: 1729–1794.

Dapples, E. C. 1942. The effect of macro-organisms upon near-shore marine sediments. J. Sediment. Petrol. 12: 118–126.

Emery, K. O. 1960. The sea off Southern California. John Wiley and Sons, New York. 366 p.

Emery, K. O. and **J. Hülsemann.** 1962. The relationships of sediments, life and water in a marine basin. Deep-Sea Res. 8: 165–180.

Fenschel, T. M. and **R. J. Riedl.** 1970. The sulfide system: a new biotic community underneath the oxidized layer of marine sand bottoms. Mar. Biol. 7: 255–268.

Gill, J. R. and **W. A. Cobban.** 1960. The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming. U.S. Geol. Surv. Prof. Pap. 393-A, 73 p.

Gross, M. G., S. M. Gucluer, J. S. Creager, and **W.A. Dawson.** 1963. Varved marine sediments in a stagnant fjord. Science 141: 918–919.

Gucluer, S. M. and **M. G. Gross.** 1964. Recent marine sediments in Saanich Inlet, a stagnant marine basin, Limnol. Oceanog. 9: 359–376.

Hartman, O. and **J. L. Barnard.** 1958. The benthic fauna of the deep basins off Southern California. Allan Hancock Pacific Expeditions, v. 22, no. 1, 67 p.

——— 1960. The benthic fauna of the deep basins off Southern California. Allan Hancock Pacific Expeditions, v. 22, no. 2, p. 69–297.

Hjulstrom, F. 1939. Transportation of detritus by moving waters. *In* P. D. Trask [ed.] Recent marine sediments. Tulsa, Okla., Am. Assoc. Pet. Geol. p. 5–31.

Hülsemann, J. and **K. O. Emery.** 1961. Stratification in recent sediments of Santa Barbara Basin as controlled by organisms and water character: J. Geol. 69: 279–290.

Mello, J. E. 1969. Foraminifera and stratigraphy of the upper part of the Pierre Shale and the lower part of the Fox Hills Sandstone (Cretaceous) North-Central South Dakota. U.S. Geol. Serv. Prof. Pap. 611, 121 p.

Moore, D. G. and **P. C. Scruton.** 1957. Minor internal structures of some Recent unconsolidated sediments. Am. Assoc. Pet. Geol. Bull. 41: 2723–2751.

Moore, H. B. 1931. The muds of the Clyde Sea area. III. Chemical and physical conditions; rate and nature of sedimentation; and fauna. J. Mar. Biol. Assoc. U. K. 17: 325–358.

Nota, D. J. G. 1958. Sediments of the western Guiana shelf. Medel. Landbouwhogesh. Wageningen-Nederland, v. 58. H. Veenman, Wageningen 98 p.

Parker, R. H. 1964a. Zoogeography and ecology of macroinvertebrates of Gulf of California and continental slope of western Mexico. *In* T. J. van Andel, and G. G. Shor. [eds.] Marine geology of Gulf of California. Am. Assoc. Pet. Geol. Mem. 3, p. 331–376.

——— 1964b. Zoogeography and ecology of some macroinvertebrates, particularly molluscs, in the Gulf of California and the continental slope off Mexico. Vidensk. Medd. Dan. Naturhist. Foren. Bind. 126: 1–178.

Pearse, A. S. and **G. Gunter.** 1957. Salinity. *In* J. W. Hedgepeth [ed.] Treatise on marine ecology and paleoecology, v. 1, Ecology. Geol. Soc. Am. Mem. 67, p. 129–158.

Pike, W. S., Jr. 1947. Intertonguing marine and nonmarine Upper Cretaceous deposits of New Mexico, Arizona, and southwestern Colorado. Geol. Soc. Am. Mem. 24, 103 p.

Piper, D. J. W. 1972. Turbidite origin of some laminated mudstones: Geol. Mag. 109: 115–126.

Raff, R. A. and **E. C. Raff.** 1970. Respiratory mechanisms and the metazoan fossil record: Nature (London) 228: 1003–1005.

Reineck, H. E. 1967. Layered sediments of tidal flats, beaches, and shelf bottoms of the North Sea. *In* G. H. Lauff, [ed.] Estuaries. Am. Assoc. Adv. Sci., Washington, D.C. p. 191–206.

Revelle, R. 1950. Sedimentation and oceanography: survey of field observations. *In* 1940 E. W. Scripps Cruise to the Gulf of California. Geol. Soc. Am. Mem. 43, Part V, p. 1–6.

Rhoads, D. C. 1963. Rates of sediment reworking by *Yoldia limatula* in Buzzard's Bay, Massachusetts, and Long Island Sound. J. Sediment. Petrol. 33: 723–727.

——— 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzard's Bay, Massachusetts. J. Geol. 75: 461–476.

——— 1970. Mass properties, stability, and ecology of marine muds related to burrowing activity. *In* T. P. Crimes and J. C. Harper [eds.] Trace fossils. Geol. J. Special Issue 3, p. 391–406.

Rhoads, D. C. and **J. W. Morse.** 1971. Evolutionary and ecologic significance of oxygen-deficient marine basins. Lethaia 4: 413–428.
Rickard, L. V. 1964. Correlation of Devonian rocks in New York State. N. Y. Museum and Science Service Geol. Surv. Map and Chart Series, no. 4.
Ross, D. A., E. T. Degens, and **J. MacIlvaine.** 1970. Black Sea: recent sedimentary history. Science 170: 163–165.
Schäfer, W. 1962. Aktuo-paläontologie nach studien in der Nordsee. Waldemar Kramer, Frankfurt, 666 p.
Scruton, P. C. 1955. Sediments of the Eastern Mississippi Delta. *In* J. L. Hough and H. W. Menard [eds.] Finding ancient shorelines. Soc. Econ. Paleontol. Mineral. Spec. Publ. 3, p. 21–51.
Segerstrale, S. G. 1957. Baltic Sea. *In* J. W. Hedgepeth [ed.] Treatise on marine ecology and paleoecology, v. 1, Ecology. Geol. Soc. Am. Mem. 67, p. 751–802.
Seibold, E. 1958. Jahreslagen in Sedimenten der mittleren Adria. Geol. Rundschau 47: 100–117.
——— 1970. Nebenmeere im humiden und ariden Klimabereich. Geol. Rundschau 60: 73–105.
Strøm, K. M. 1955. Landlocked waters and the deposition of black muds. *In* P. D. Trask. [ed.] Recent marine sediments. Am. Assoc. Pet. Geol., Tulsa, p. 356–372.
Sutton, R. G. 1960. Stratigraphy of the Naples Group (Late Devonian) in Western New York. N. Y. State Mus. Sci. Ser. Bull. 380, 56 p.
——— 1963. Correlation of Upper Devonian strata in Southcentral New York. *In* V. C. Shepps [ed.] Symposium on Middle and Upper Devonian stratigraphy of Pennsylvania and adjacent states. Topogr. Geol. Surv. Gen. Geol. Rep. G39, p. 87–101.
Sutton, R. G., Z. P. Bowen, and **A. L. McAlester.** 1970. Marine shelf environments of the Upper Devonian Sonyea Group of New York. Geol. Soc. Am. Bull. 81: 2975–2992.
Theede, H., A. Ponat, K. Hiroki, and **C. Schlieper.** Studies on the resistance of marine bottom invertebrates to oxygen deficiency and hydrogen sulfide. Mar. Biol. 2: 325–337.
Twenhofel, W. H. 1939. Environments of origin of black shales. Am. Assoc. Pet. Geol. Bull. 23: 1178—1198.
van Andel, T. H. 1964. Recent marine sediments of the Gulf of California. *In* T. H. van Andel and G. G. Shor [eds.] Marine geology of the Gulf of California. Am. Assoc. Pet. Geol. Mem. 3, p. 216–310.
Van Straaten, L. M. J. U. 1959. Minor structures of some Recent littoral and neritic sediments. Geol. Mijnbouw, N.W. Ser. 21, p. 197–216.
Waage, K. 1968. The Type Fox Hills Formation, Cretaceous (Maestrichtian) South Dakota; Part 1. Stratigraphy and paleoenvironments. Peabody Mus. Nat. Hist. Yale Univ. Bull. 27, 175 p.
Walker, R. G. and **R. G. Sutton.** 1967. Quantitative analysis of turbidites in the Upper Devonian Sonyea Group, New York. J. Sediment. Petrol. 37: 1012–1022.
Zangerl, R. and **E. S. Richardson.** 1963. The paleoecological history of two Pennsylvanian black shales. Fieldiana Geol. Mem. 4, 352 p.

Unpublished Reference

Dunham, R. J. 1961. Geology of uranium in the Chadron area, Nebraska and South Dakota. Ph.D. dissertation, Yale Univ., 243 p.

The Author

Charles W. Byers. Department of Geology and Geophysics, University of Wisconsin-Madison, Madison, Wisconsin 53706.

Appendix

Locality List

Sonyea Group

No.	Name	7½-Minute Quadrangle	Latitude	Longitude
			° ′ ″	° ′ ″
42	Sturgeon Point	Angola	42 41 40	79 02 10
41	Murder Creek	Alexander	42 53 20	78 21
40	Richmond Center	Honeoye	42 48 20	77 33 40
39	Keuka East	Hammondsport	42 29	77 08 30
38	Sawmill Creek	Burdett	42 29 50	76 51 40
31	Troy Road	Ithaca East	42 24	76 28 30
30	Richford	Richford	42 21 30	76 12
29	Harford Mills	Harford	42 25	76 11 30
27	Messengerville	Marathon	42 27 30	76 04 30
26	Galatia Quarry	Marathon	42 28 30	76 01 30
25	Rabbit Road	Lisle	42 17	76 01
24	Itaska	Whitney Point	42 17 30	75 55
23	Castle Creek	Castle Creek	42 10	75 54
20	Seymour Hill	Brisben	42 16	75 39
18	Wilkens Brook	West Bainbridge	42 17 30	75 36
17	Bluestone Quarry	Sidney	42 16 30	75 23
15	Burns Road	Ithaca East	42 24 30	76 28
12	Hunt's Creek Quarry	Marathon	42 29 30	76 02 30
11	Triangle	Whitney Point	42 21	75 53 30
10	Ockerman Brook	Greene	42 17	75 50 30
9	Curtis Swamp	Greene	42 18	75 46
8	Greene	Brisben	42 18 30	75 44 30
7	North Pond	Oxford	42 26	75 30
6	Guilford	Guilford	42 27 30	75 28
5	Bainbridge	Sidney	42 17 30	75 27 30
4	Carr's Creek	Unadilla	42 17 30	75 17 30
3	Sidney Center	Unadilla	42 17 30	75 16
2	East Sidney	Franklin	42 19 30	75 14
1	Sherman Hill	Franklin	42 19	75 12 30

Pierre Shale and Fox Hills Formation

Red Bird Area

1. Southeast end of gravel-capped mesa, 3 miles east of Red Bird; in NW ¼, Sec. 20, T 38N, R 61W, Niobrara County, Wyoming.
   Sharon Springs Member: Samples SS1–SS15.
2. Western gullies in slope below mesa in Locality 1.
   Gammon Ferruginous Member: Samples G1–G4. Niobrara Formation: Samples N1–N2.
3. Gully exposures along Traverse A of Gill and Cobban (1966); in N ½, Sec. 23, T 38N, R 62W, Niobrara County, Wyoming.
   Mitten Black Shale Member: Samples M1–M2.
   Red Bird Silty Member: Samples RBS1–RBS2.

Lower Unnamed Shale Member: Samples LUS1–LUS5.

Upper Unnamed Shale Member: Samples UUS1–UUS2.

Fox Hills Formation: Samples FH1–FH3.

Chadron Area

4. Slope on ridge west of road; in SW ¼, Sec. 16, T 35N, R 47W, Shannon County, South Dakota.

Sharon Springs Member: Samples CSS1–CSS5.

5. Gully system at base of ridge in Locality

Gammon Ferruginous Member: Samples CG1–CG4.

Type Fox Hills Area

6. Roadcut on Whitehorse Road, 3.5 miles east of South Dakota Highway 63, Dewey County, South Dakota.

Mobridge Member: Sample Mol.

7. River breaks of north bank of Moreau River west of South Dakota Highway 63; NE ¼ SE ¼, Sec. 6, T 14N, R 24E, Dewey County, South Dakota.

Mobridge Member: Sample Mo2.

8. Ditch along west side of South Dakota Highway 63; in SW ¼ SW ¼, Sec. 32, T 15N, R 24E, Dewey County, South Dakota.

Elk Butte Member: Sample EB2.

9. Northern bluff of Moreau River; in SW ¼ SW ¼ NW ¼, Sec. 35, T 15N, R 21E, Ziebach County, South Dakota.

Elk Butte Member: Sample EB1.

Irish Creek Lithofacies: Samples IC1–IC5.

10. South bank of Moreau River; in NE ¼, Sec. 3, T 14N, R 20E, Ziebach County, South Dakota.

Irish Creek Lithofacies: Sample IC6.

11. Breaks in southern bluffs of Moreau River directly south of Locality 10; in S ½ NE ¼, Sec. 3, T 14N, R 20E, Ziebach County, South Dakota.

Irish Creek Lithofacies–Sample IC7.

12. Break in bluffs north of Moreau River, just west of South Dakota Highway 63; in E ½ SW ¼, Sec. 32, T 15N, R 24E, Dewey County, South Dakota.

Little Eagle Lithofacies. Samples LE1–LE14.

13. Exposure in river bluffs north of Moreau River, just east of South Dakota Highway 63; in SW ¼ SE ¼, Sec. 32, T 15N, R 24E, Dewey County, South Dakota.

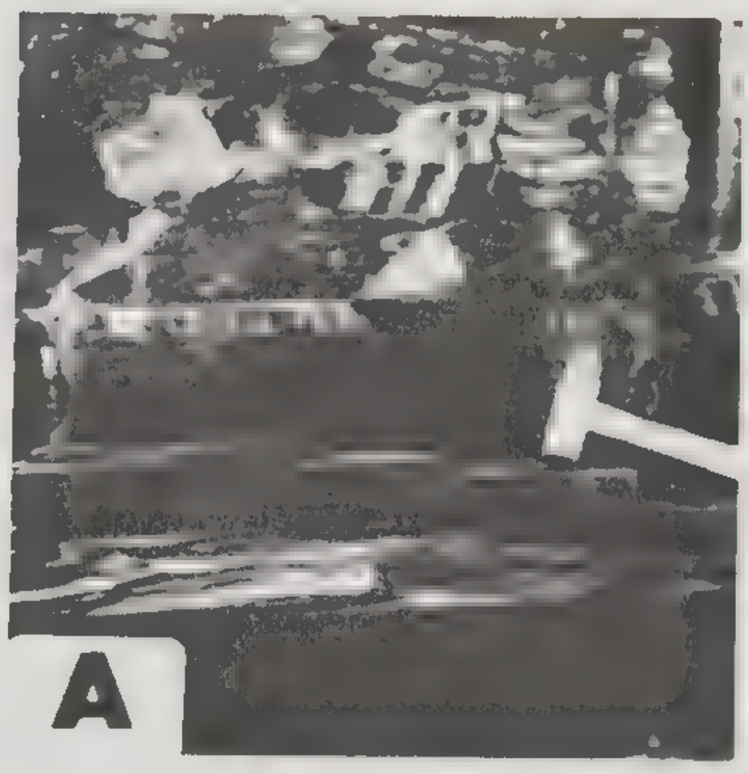
Little Eagle Lithofacies: Sample LE15.

14. Badlands slope south of Moreau River; in NE ¼ SW ¼, Sec. 22, T 14N, R 20E, Ziebach County, South Dakota.

Bullhead Lithofacies: Sample B1.

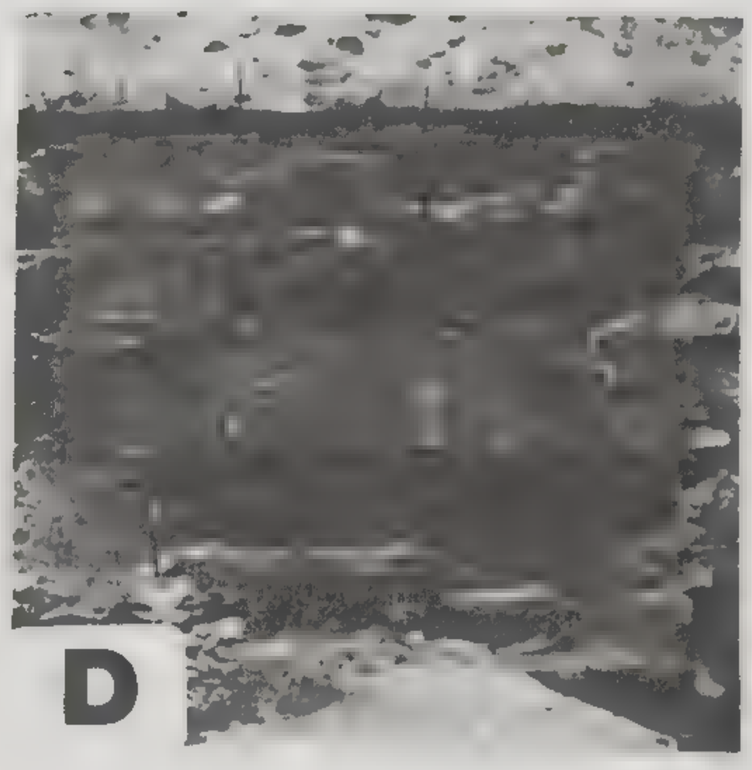
Figures 16–22

Fig. 16
A. Middlesex Shale, Locality 42.
B. Sawmill Creek Shale, Locality 30: repetitive interbedded silts and black shale.
C. Montour Shale, Locality 7.
D. Sawmill Creek Shale, Locality 17: dark shale zone under massive sand in center of photo. Thick marine sands and redbeds visible immediately above shale.
E. Solemarked silt from Locality 15.


A

B

C


D

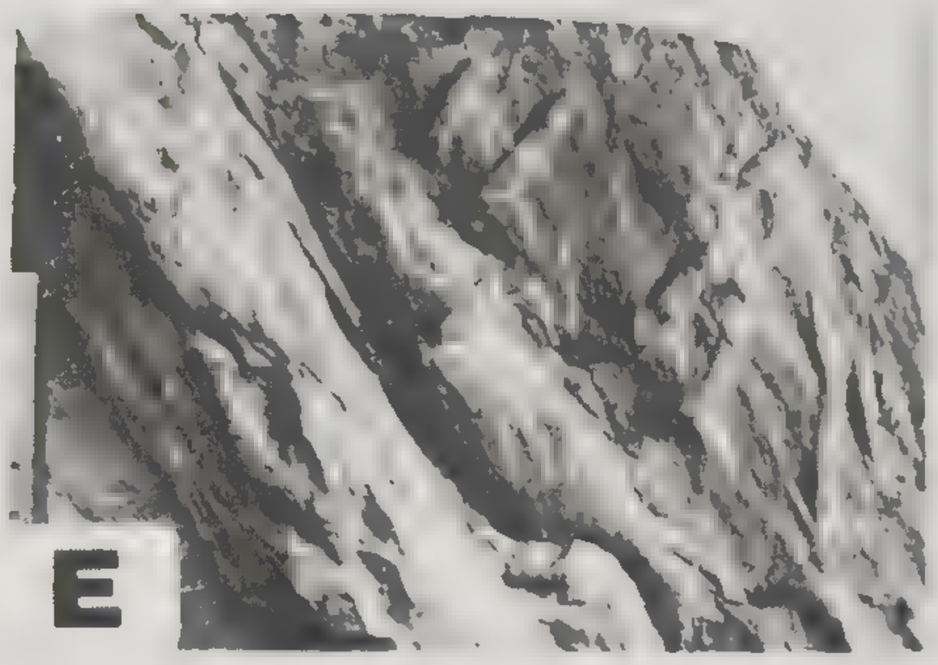

E

Fig. 17
A. Middlesex Shale, Locality 42 (metric scale).
B. Close-up photo of sample in A (metric scale). Note very fine lamination.
C, D, E. Change in lamination in Middlesex Shale, Locality 42 (all figures 25×)
C. Basal Middlesex.
D. Middle Middlesex.
E. Upper Middlesex.
F. Middlesex Shale, Locality 39 (metric scale).
G. Middlesex Shale, Locality 40 (metric scale). Note wavy and irregular silt laminae.
H. Sawmill Creek Shale, Locality 25 (metric scale). Laminated shale deformed by loading.
I. Middlesex Shale, Locality 38 (metric scale). Laminated silt changes to laminated shale at sharp, horizontal contact.
J. Montour Shale, Locality 1 (metric scale). Parting lineation.
K. Montour Shale, Locality 6 (metric scale).
L. Sawmill Creek Shale, Locality 17 (metric scale). Silt-shale contact cross-laminated.

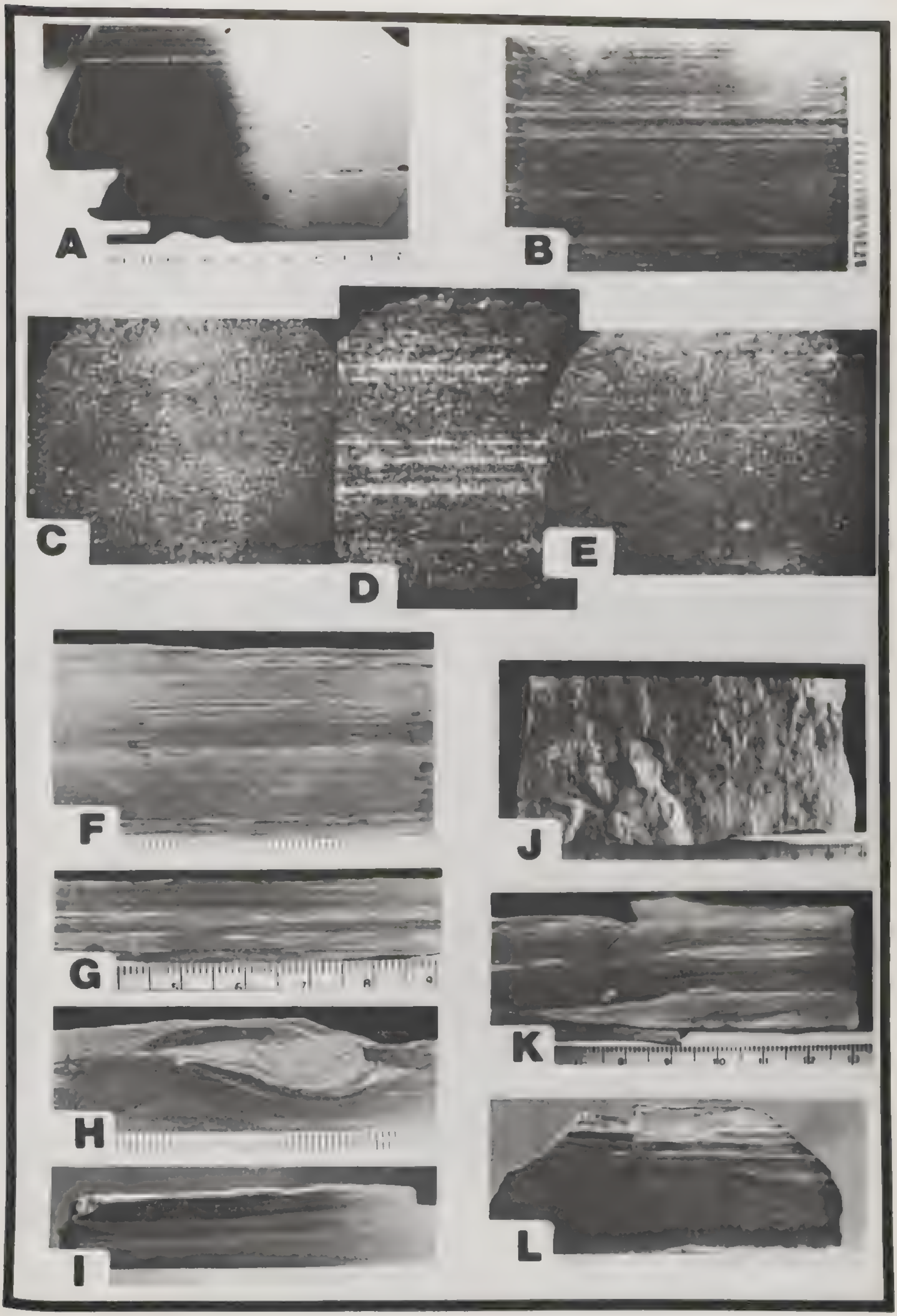
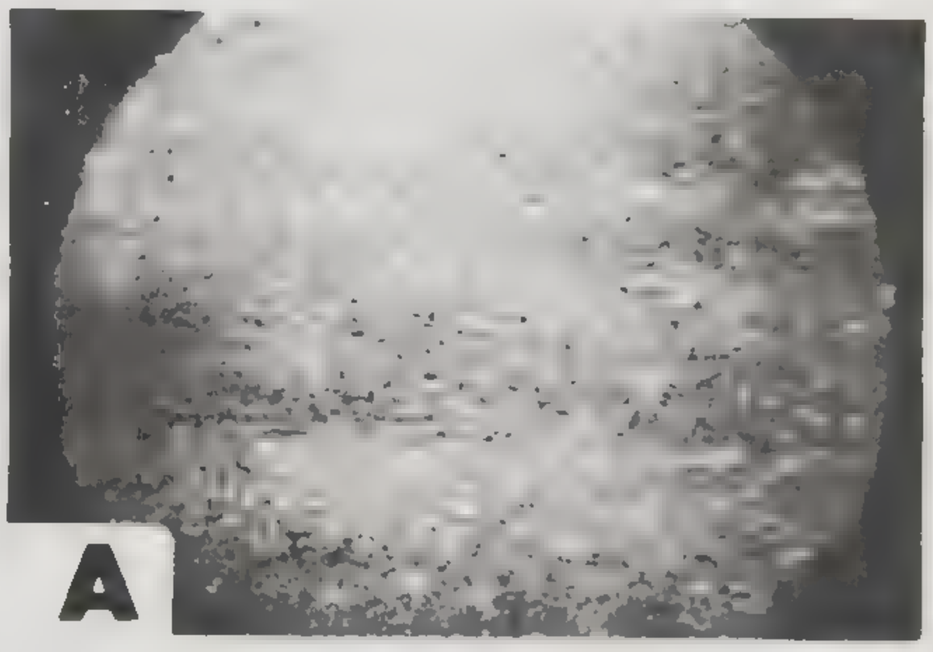
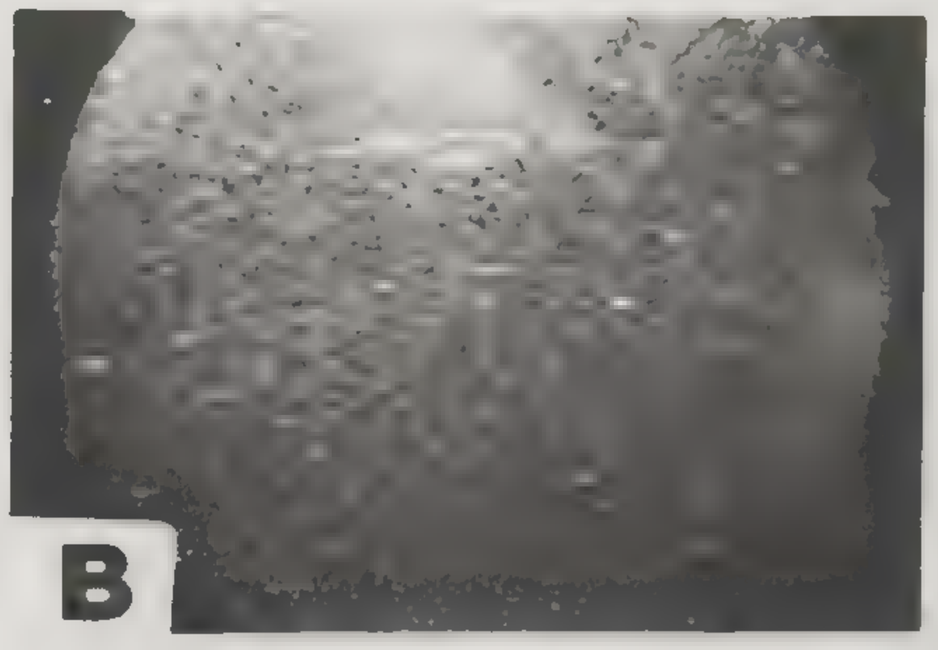

A
B
C
D
E
F
G
H
I
J
K
L

Fig. 18
A. Uppermost Niobrara Formation, Sample N2, Red Bird Section (12×).
B. Gammon Member of Pierre Shale, Sample CG1, Chadron, Nebraska (12×).
C, D. Sharon Springs Member of Pierre Shale, Red Bird Section (both figures 25×). Note increased horizontality of fabric (lack of bioturbation).
C. Sample SS1.
D. Sample SS10.
E. Sharon Springs Member of Pierre Shale, Sample CSS3, Chadron, Nebraska (25×).


A


B

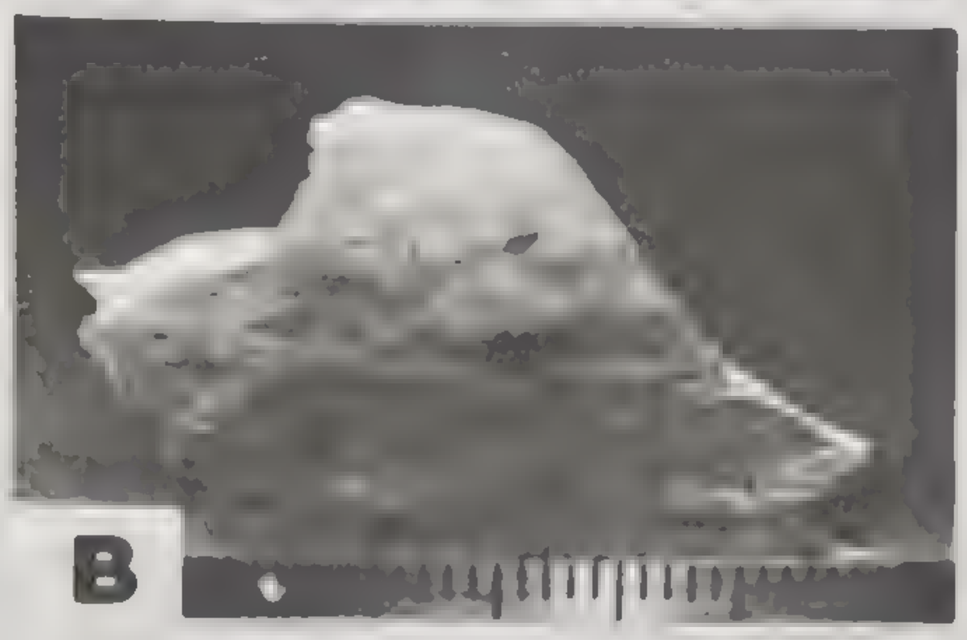
C

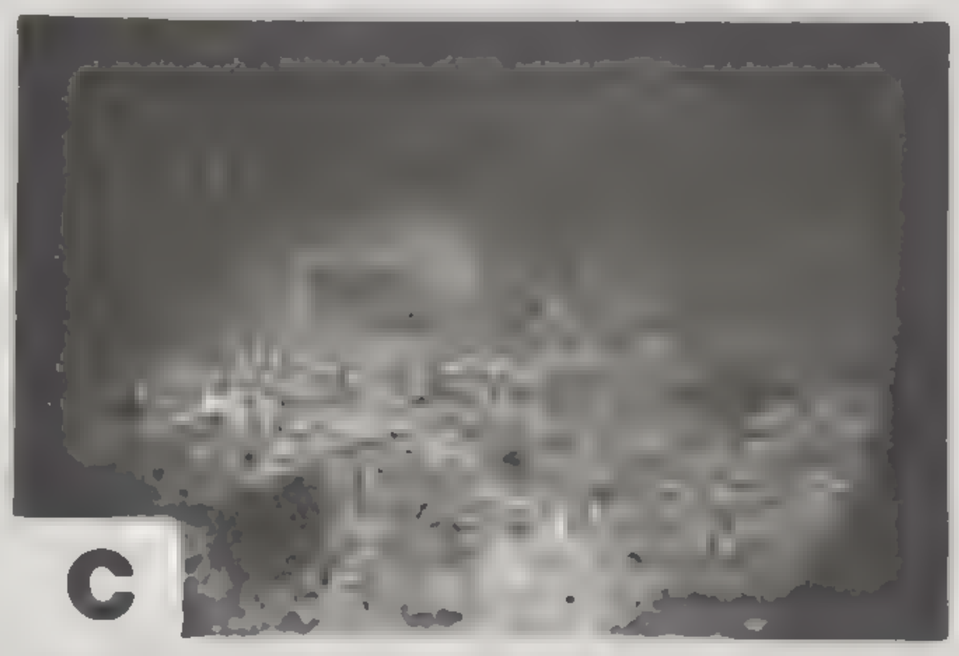
D

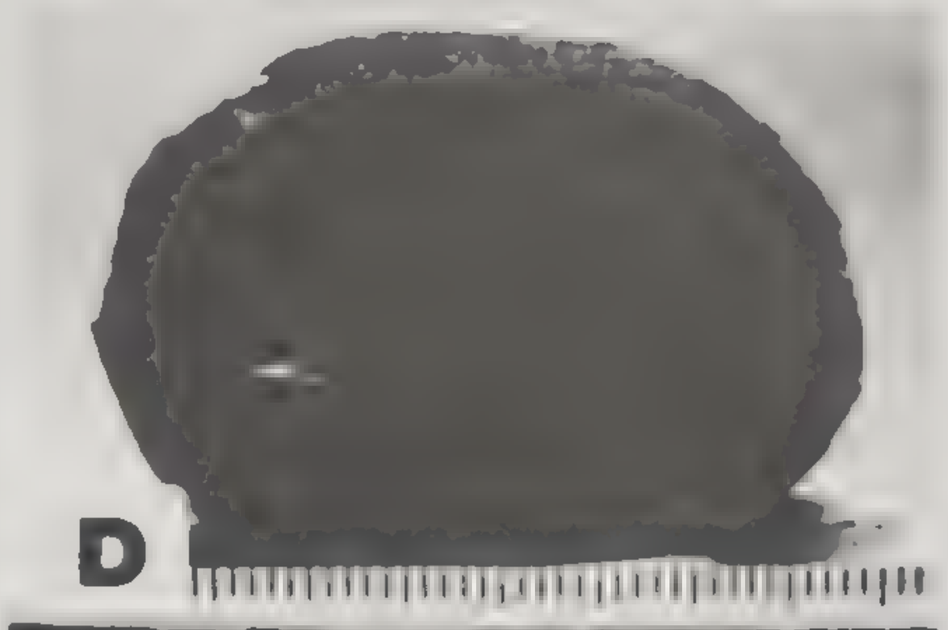
E

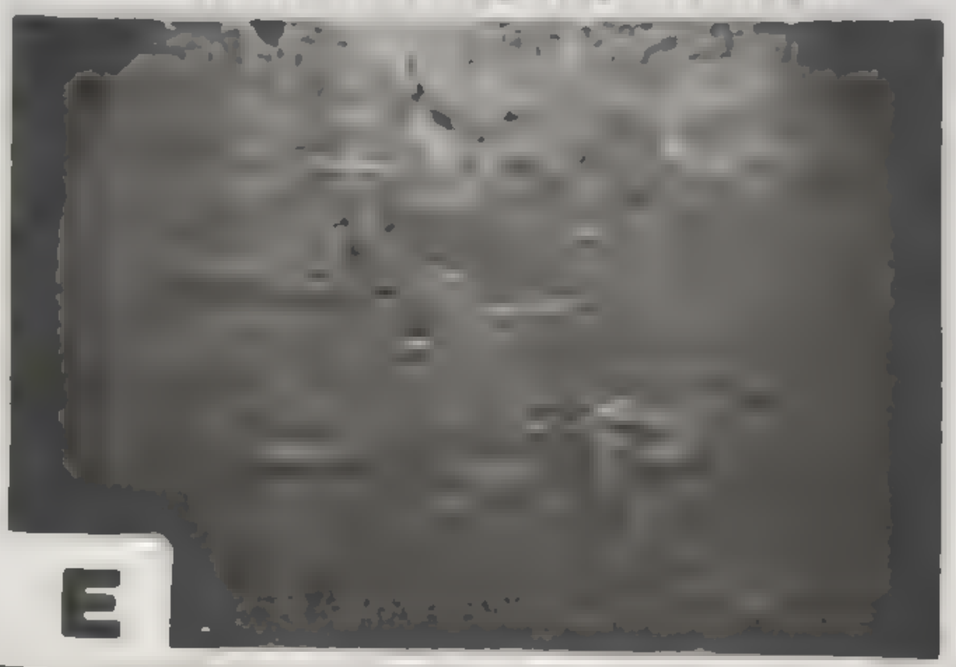
Fig. 19
A. Mitten Member of Pierre Shale, Sample M2, Red Bird Section (25×). Note absence of lamination in bioturbate fabric.
B. Red Bird Silty Member of Pierre Shale, Sample RBS1, Red Bird Section (metric scale).
C. Photomicrograph of sample in B (12×).
D. Lower Unnamed Shale Member of Pierre Shale, Sample LUS4, Red Bird Section (metric scale).
E. Lower Unnamed Shale Member of Pierre Shale, Sample LUS 2, Red Bird Section (12×).
F, G, H. Stratigraphic gradient of decreasing bioturbation in Upper Unnamed Shale Member of Pierre Shale and basal Fox Hills Formation (metric scale).
F. Sample UUS1, Red Bird Section.
G. Sample UUS 2, Red Bird Section.
H. Sample FH1, Red Bird Section.

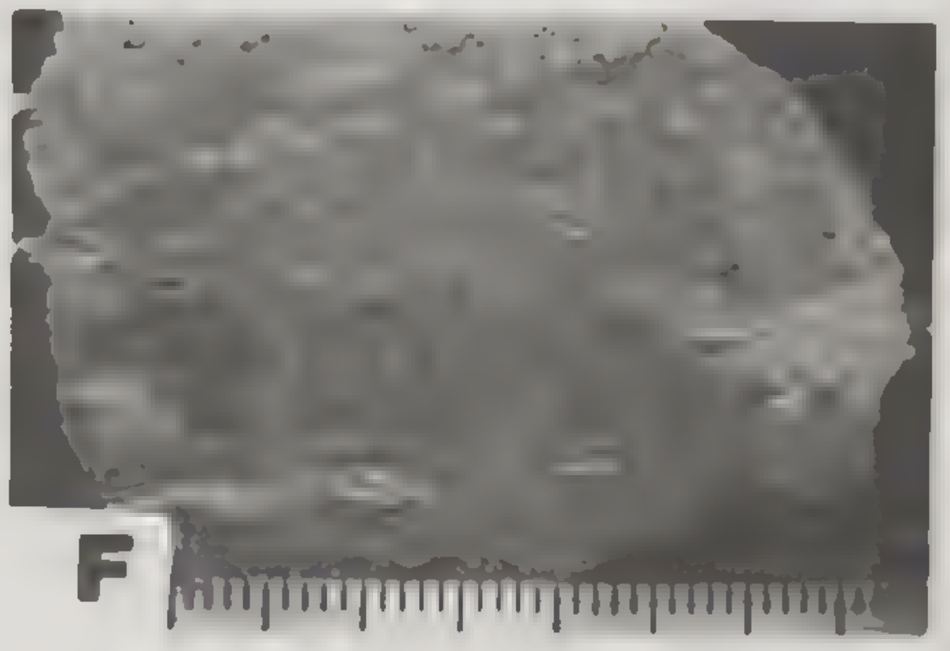
A

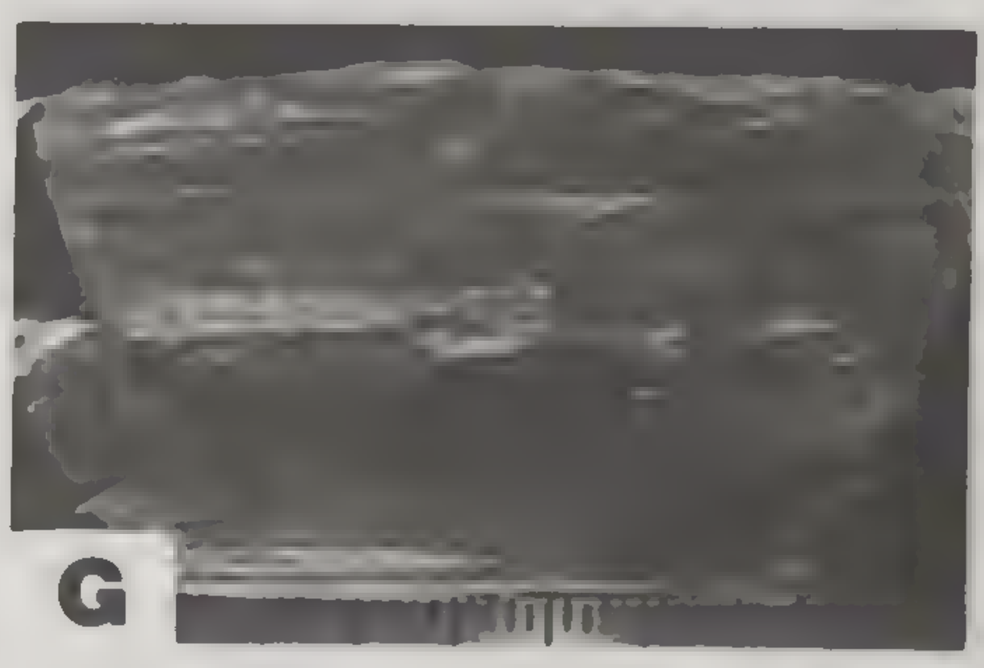

B


C


D


E


F


G

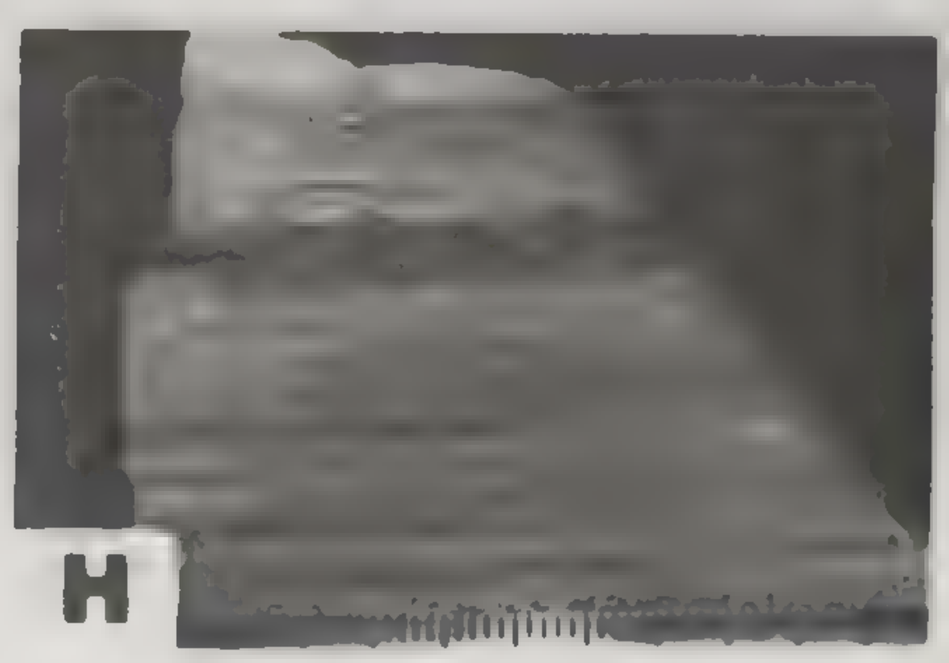
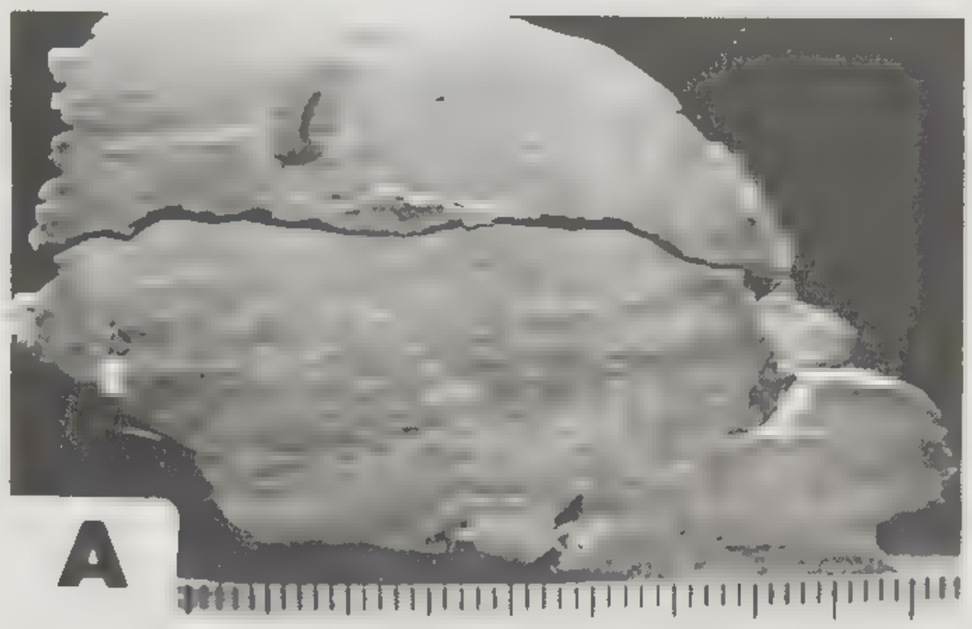
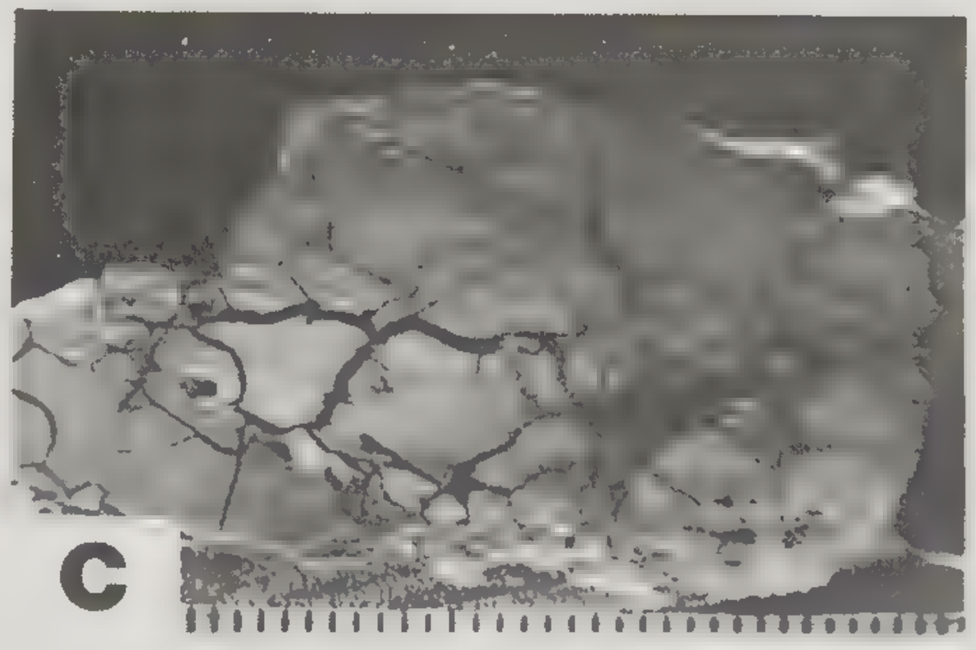
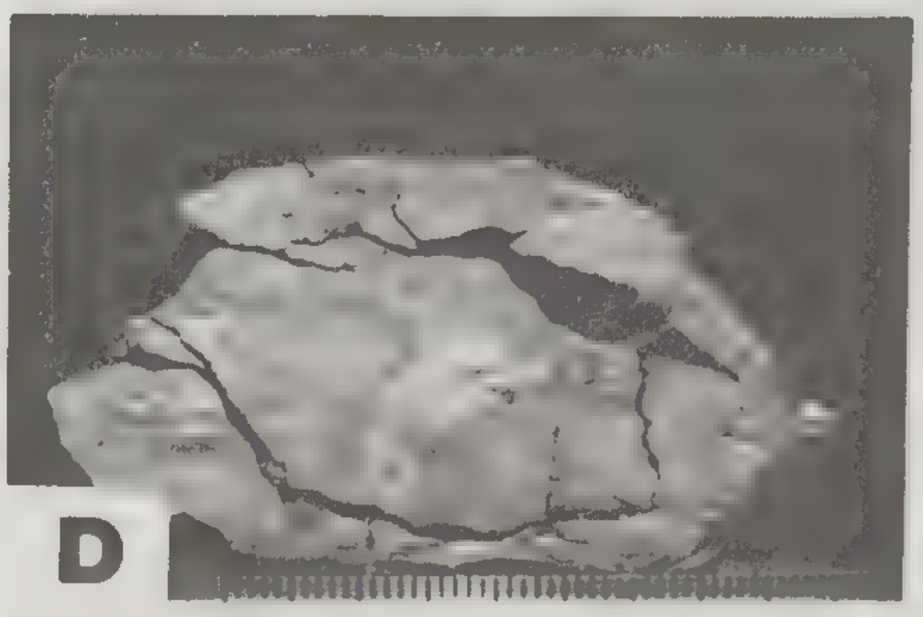

H

Fig. 20
A. Elk Butte Member of Pierre Shale, Sample EB2, Fox Hills Type Area (metric scale).
B. Photomicrograph of sample in A (12×)
C, D, E, F. Trail City Member of Fox Hills Formation, Fox Hills Type Area (metric scale). Stratigraphic gradient of increasing silt upward from Elk Butte contact
C. Irish Creek Lithofacies, Sample IC2, dark bioturbate mudstone.
D. Irish Creek Lithofacies, Sample IC4, bioturbate silty mudstone.
E. Little Eagle Lithofacies, Sample LE5, bioturbate siltstone
F. Irish Creek Lithofacies, Sample IC6, intact silt layers in dark claystone


A

B


C


D

E

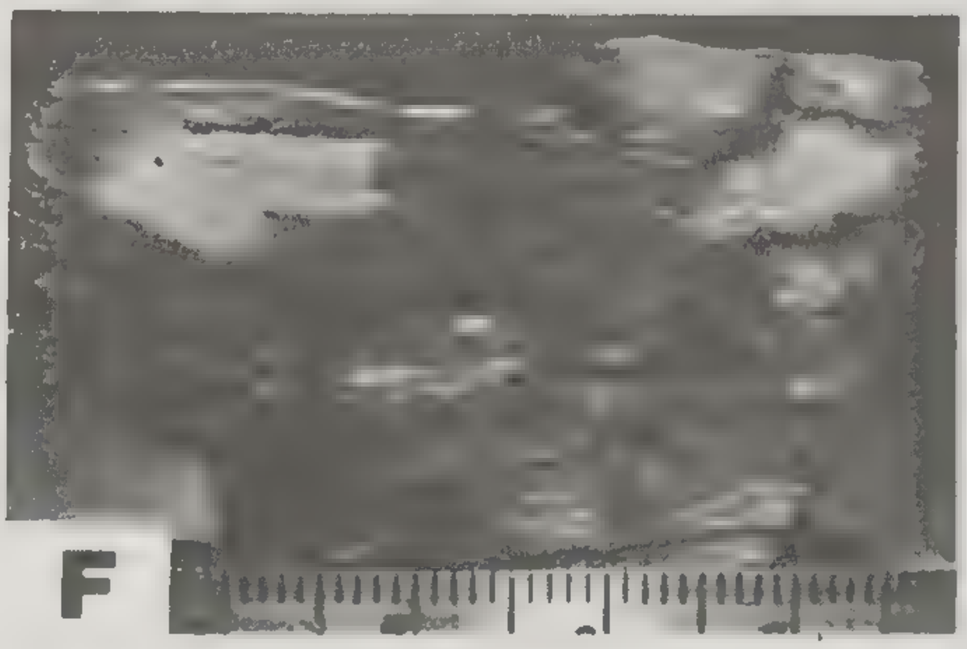

F

Fig. 21

A–E. Dark, clay-filled burrows.

A. Bullhead Lithofacies of Fox Hills Formation, Fox Hills Type Area (metric scale). Laminated siltstone with occasional dark burrows; silt halos around clay filling.

B. Bullhead Lithofacies of Fox Hills Formation, Fox Hills Type Area (metric scale). Strongly bioturbate siltstone with very abundant dark burrows.

C. Dark burrow in Montour Shale (metric scale).

D. Dark burrow in Little Eagle Lithofacies (metric scale).

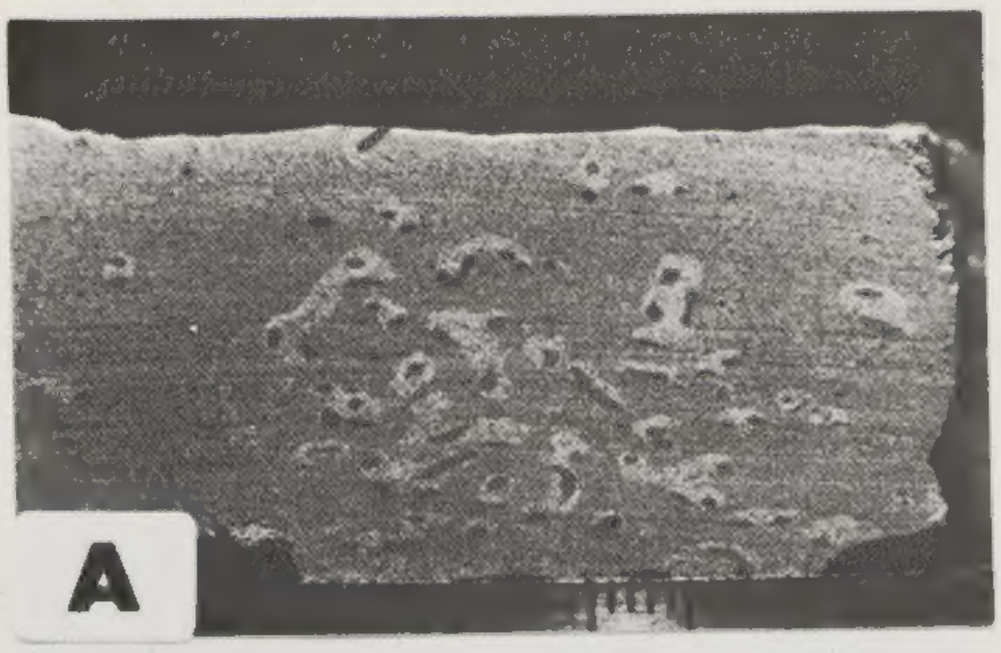
E. Dark burrow in Little Eagle Lithofacies, showing backfill structure (metric scale).

F–H. Light, silt-filled burrows.

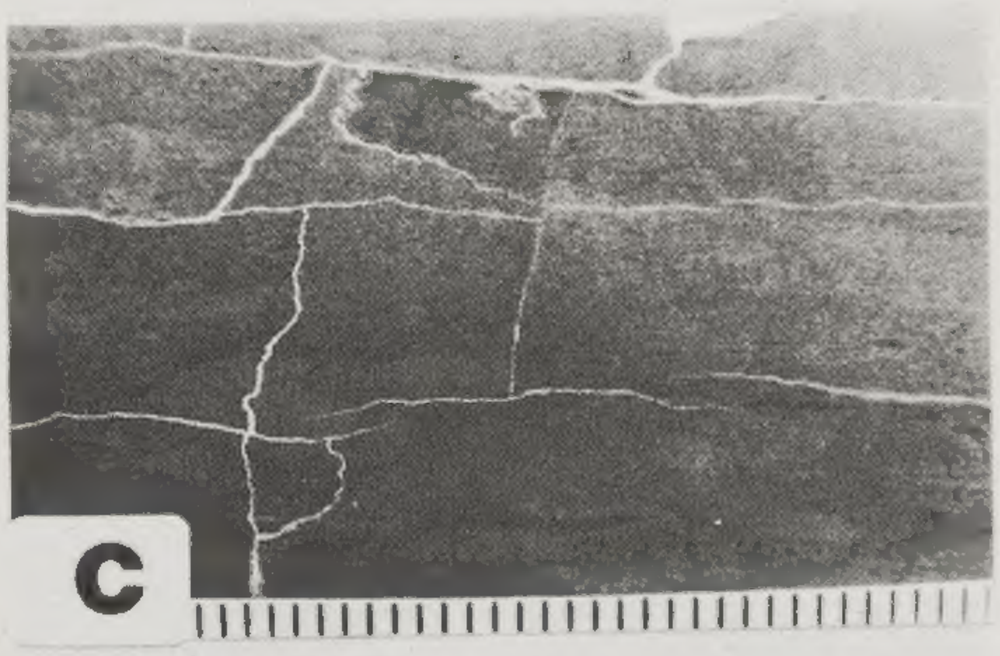
F. Light burrow from silt layer extending into underlying bioturbate mudstone, in Montour Shale (metric scale).

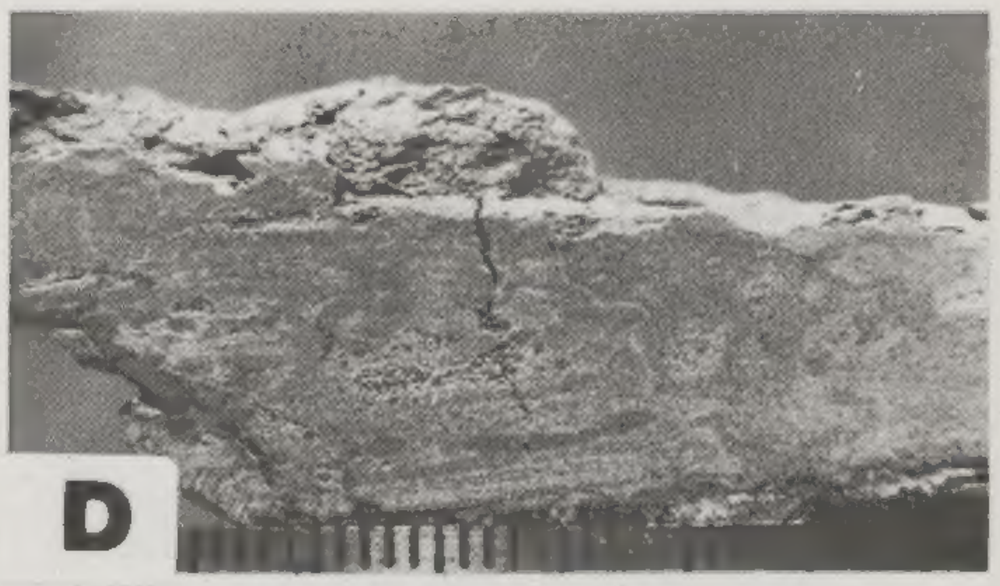
G. Light burrow in cross-section, Triangle Formation, Sonyea Group (metric scale).

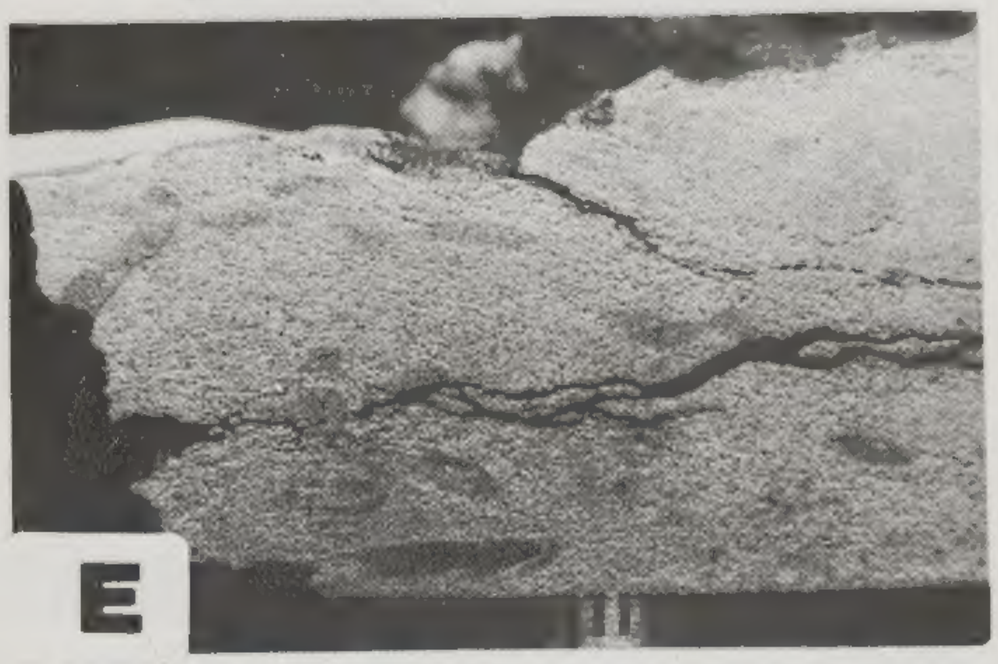
H. Light burrow in cross-section, Upper Unnamed Shale Member of Pierre Shale (metric scale).

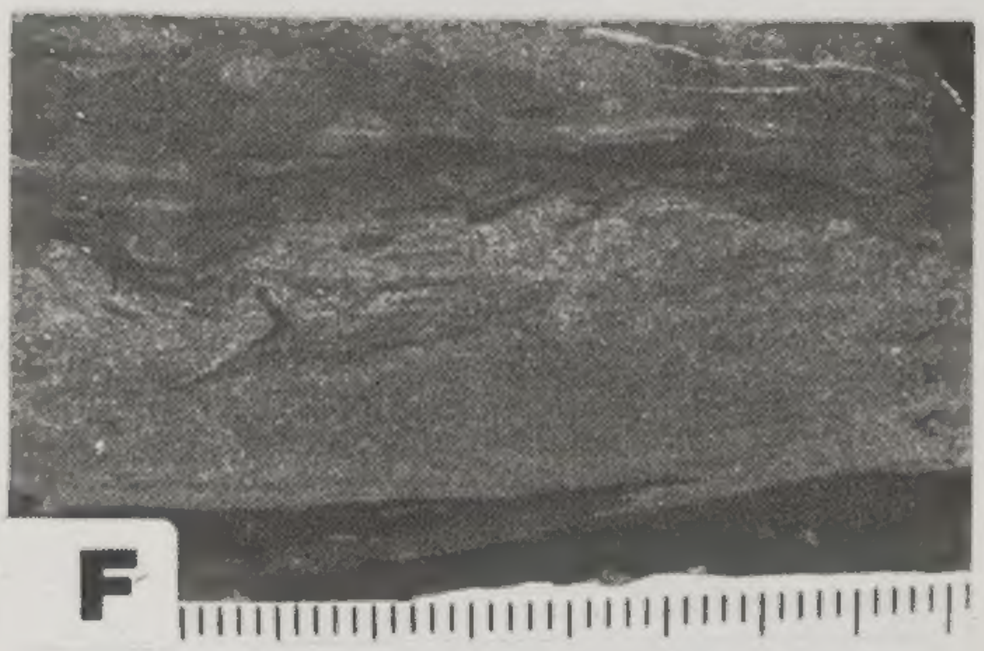

A

B


C


D


E


F

G

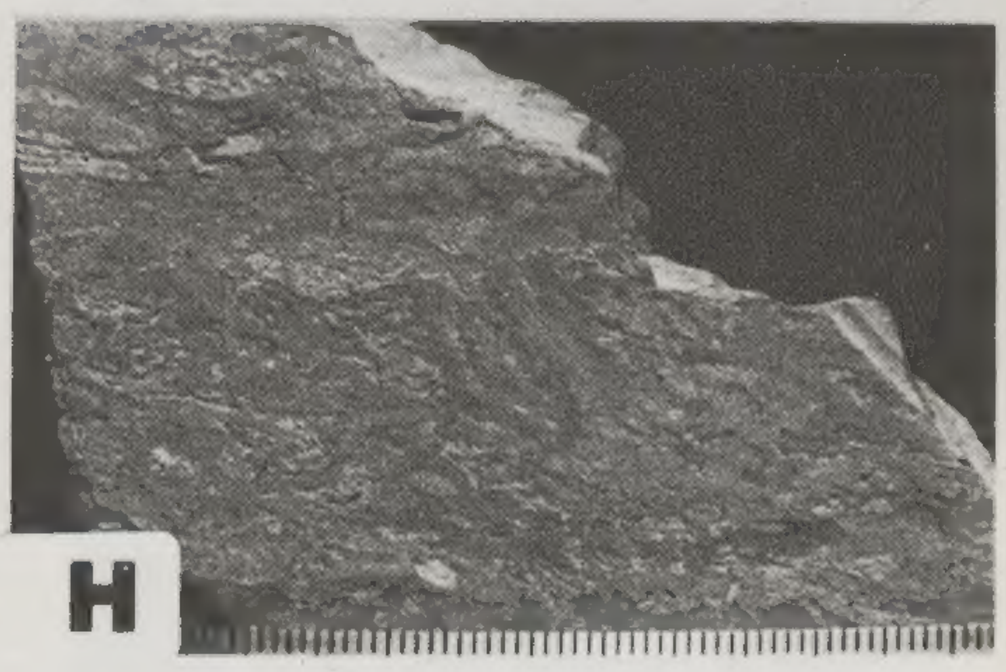

H

Fig. 22

A–C. Stratigraphic gradient in bioturbation at Locality 29 (metric scales).

A. Undisturbed black shale at Sawmill Creek Horizon (dark objects are plant debris).

B. Laminated silty shale partially broken by burrowing, in Triangle Formation below Sawmill Creek.

C. Strongly bioturbate mudstone from Triangle Formation, below sample in B.

D–E. Equivalent facies in the Triangle Formation and the Sawmill Creek Shale: dark bioturbate mudstone with occasional body fossils (metric scales).

D. Triangle Formation, Locality 29.

E. Sawmill Creek Shale, Locality 20.

F–H. West-to-East gradient of bioturbation in the Montour Shale (metric scales).

F. Laminated black shale, Locality 15.

G. Partly mottled silt layers in bioturbate mudstone, Locality 12.

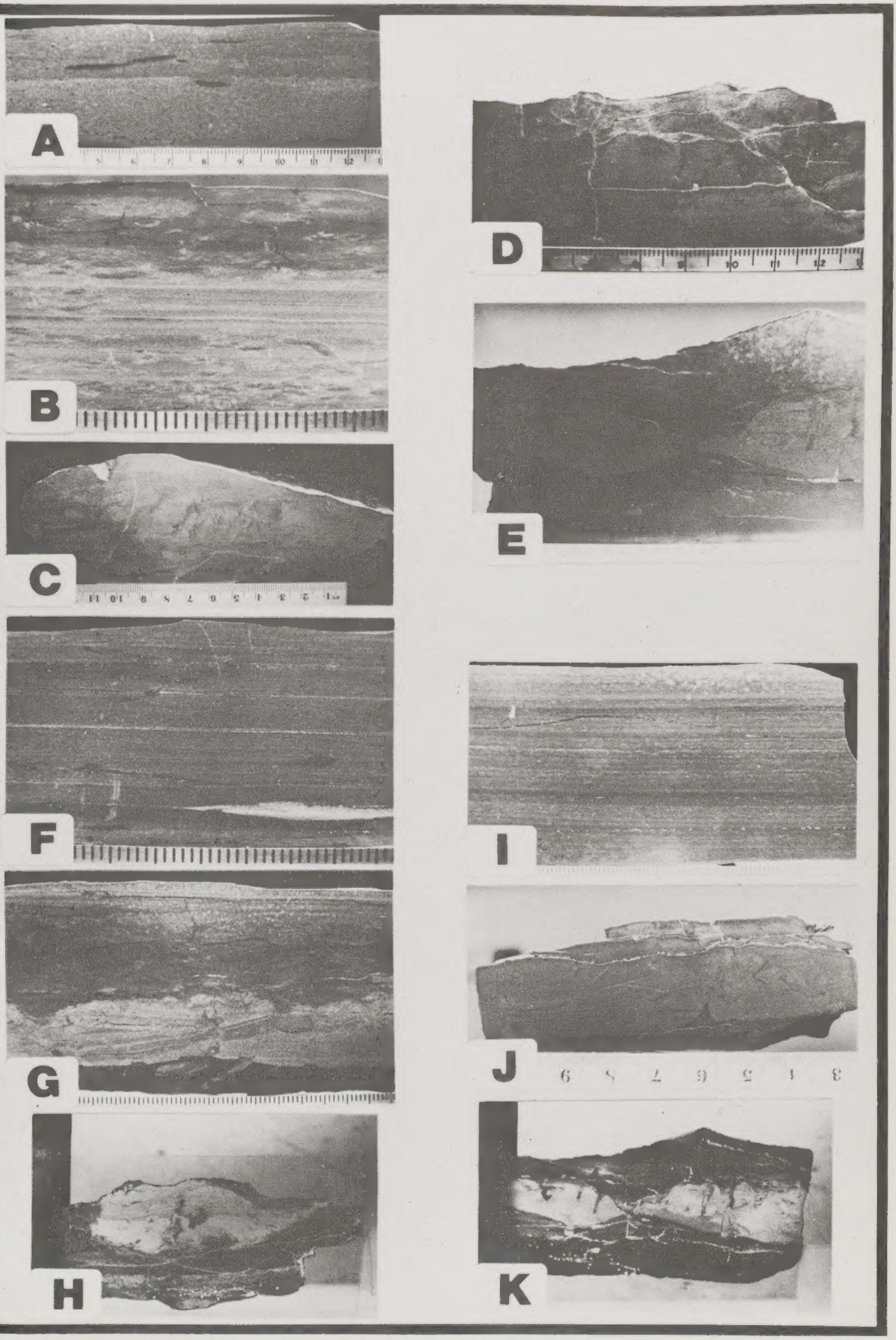
H. Strongly mottled silty mudstone, Locality 11.

I–K. West-to-East gradient in bioturbation in the Sawmill Creek Shale (metric scales).

I. Laminated black shale, Locality 26.

J. Slightly mottled silt layers, Locality 23.

K. Strongly mottled silt layer in bioturbate mudstone, Locality 20.


A
B
C
D
E
F
G
H
I
J
K